VLT/UVES Abundances in Four Nearby Dwarf Spheroidal Galaxies: I. Nucleosynthesis and Abundance Ratios [1]

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ABSTRACT

We have used the Ultra-Violet Echelle Spectrograph (UVES) on Kueyen (UT2) of the VLT to take spectra of 15 individual red giants in the Sculptor, Fornax, Carina and Leo I dwarf spheroidal galaxies (dSph). We measure the abundances of alpha, iron peak, first s-process, second s-process and r-process elements. No dSph giants in our sample show the deep mixing abundance pattern (O and sometimes Mg depleted while Na and Al are enhanced) seen in nearly all globular clusters. At a given metallicity the dSph giants exhibit lower [el/Fe] abundance ratios for the alpha elements than stars in the Galactic halo. The low alpha abundances at low metallicities can be caused by a slow star formation rate and contribution from Type Ia SN, and/or a small star formation event (low total mass) and mass dependent Type II SN yields. In addition,

[1] Based on Ultraviolet-Visual Echelle Spectrograph observations collected at the European Southern Observatory, Paranal, Chile, within the observing programs 65.N-0378 and 66.B-0320

Leo I and Sculptor exhibit a declining even-Z [el/Fe] pattern with increasing metallicity, while Fornax exhibits no significant slope. In contrast, Carina shows a large spread in the even-Z abundance pattern, even over small metallicity ranges, as might be expected from a bursting star formation history.

The metal-poor stars in these dSph galaxies ([Fe/H] < -1) have halo-like s&r-process abundances, but not every dSph exhibits the same evolution in the s&r-process abundance pattern. Carina, Sculptor and Fornax show a rise in the s/r-process ratio with increasing metallicity, evolving from a pure r-process ratio to a solar-like s&r-process ratio. On the other hand, Leo I, appears to show an r-process dominated ratio over the range in metallicities sampled. At present, we attribute these differences in the star formation histories of these galaxies.

Comparison of the dSph abundances with those of the halo reveals some consistencies with the Galactic halo. In particular, Nissen & Shuster (1997) found that their metal-rich, high R_{max} high z_{max} halo stars exhibited low [alpha/Fe], [Na/Fe] and [Ni/Fe] abundance ratios. In the same abundance range our dSph exhibit the same abundance pattern supporting their suggestions that disrupted dSph's may explain up to 50% of the metal-rich halo. Unfortunately, similar comparisons with the metal-poor Galactic halo have not revealed similar consistencies suggesting that the majority of the metal-poor Galactic halo could not have been formed from objects similar to the dSph studied here.

We use the dSph abundances to place new constraints on the nucleosynthetic origins of several elements. We attribute differences in the evolution of [Y/Fe] in the dSph stars versus the halo stars to a very weak AGB or SN Ia yield of Y (especially compared to Ba). That a lower and flatter Ba/Y ratio is seen in the halo is most likely due to the pattern being erased by the large metallicity dispersion in the halo. Also, we find [Cu/Fe] and [Mn/Fe] are flat and halo-like over the metallicity city range $-2 <$ [Fe/H]< -1.2, and that the [Cu/alpha] ratios are flat. Combining these abundances with knowledge of the age spread in these galaxies suggests that SN Ia are not the main site for the production of Cu (and Mn) in very metal-poor stars. We suggest that metallicity dependent SN yields may be more promising.

Subject headings: galaxies: abundances, dwarf galaxies, individual (Sculptor, Fornax, Carina, Leo I) stars: abundances

1. Introduction

Hierarchical structure formation models predict that massive galaxies formed through continuous accretion of numerous satellites, a process that, at a lower rate, should be continuing until today. One testable prediction is that the Galactic halo should have been formed through many minor merger events. Another is the number of low-mass satellites that should be observable today around the Galaxy (White & Rees 1978, Moore et al. 1999, Klypin et al. 1999). Indeed both the Galaxy and M31 contain at least one clear remnant of a dwarf galaxy accretion event: The tidal debris of the Sagittarius dwarf spheroidal (dSph) galaxy (Ibata et al. 1994) and a giant stream of metal-rich stars within the halo of M31 (Ibata et al. 2001). Less pronounced streams are more difficult to detect but may stand out kinematically and in terms of abundances (e.g., Helmi et al. 1999). It has also been suggested that the outer halo globular clusters with their predominantly red horizontal branches did not originally form in the Galaxy but were accreted from dwarf satellites (e.g., van den Bergh 2000).

Thus how did the Galactic halo form, and what role did the accretion of dSph galaxies play? If we consider ages, dSphs can plausibly have contributed significantly to the build-up of the Galactic halo, since the ages of their oldest detectable populations have been found to be indistinguishable from the oldest halo globular clusters within the measurement accuracy. An alternative approach is to accurately *measure* the dSph chemical evolution, as preserved in stellar heavy element abundance patterns, and compare that with the Galactic halo chemical evolution. This has been done for only a small samples of stars in a few nearby dSphs. The chemical evolution picture presented by Shetrone et al. (2001) is that the metal-poor giants among the smallest dSphs (Draco, Ursa Minor and Sextans) have an abundance pattern that is NOT consistent with that found in the majority of Galactic halo stars.

Dwarf spheroidal galaxies can also contribute to our understanding of the nucleosynthesis of the elements. The difference in their star formation histories and environments allow us to de-couple and test some of the assumptions made in interpreting the Galactic halo abundance patterns. For example, the formation of even Z elements and r-process elements are assumed to occur in SN II while the s-process is thought to originate in AGB stars and iron peak elements from SN Ia. If the star formation rate, and hence the chemical evolution, is slower in dSph then we should see a larger effect of metal-poor SN Ia and AGB stars than would be seen in the Galactic halo abundance patterns. In addition, because of the isolation of the dSph environment we can test closed box models of chemical evolution and look for the affects of star formation bursts and a slow star formation. For example, examination of the formation of first and second peak s-process elements (e.g., Y/Ba) are hampered in the halo because of its mixed metallicity population (e.g., see McWilliam 1997). Chemical evolution in the halo occurred very rapidly and by the time AGB stars begin to contribute to the ISM in the Galactic Halo there is a broad range of metallicities ($-3 <$ [M/H] < -1) in those AGB stars. Studying Ba and Y abundances in different environments can reveal new constraints on those elements nucleosynthetic origins. As another example of constraining nucleosynthetic origins of different elements, Cu and Mn have been thought to be primarily produced in SN Ia since Cu and Mn in the Galactic halo stars mirror the alpha-element abundances (Matteucci et al. 1993, Samland 1998, Nakamura et al. 1999), and yet other sources for Cu have been discussed in the literature (e.g., Timmes et al. 1995). Thus, in the halo stars, it is virtually impossible to distinguish SN Ia, from AGB, from metallicity dependent SN II nucleosynthetic sources, whereas it may be possible to disentangle these sources with dSph abundance patterns.

In this paper, we sample four southern dSph galaxies that have not been previously examined: Carina, Fornax, Sculptor, and Leo I. Sculptor has a mean age similar to that of a Galactic globular cluster, but that there was probably a spread in age of at least 4 Gyr (e.g. Monkiewicz et al. 1999). From low resolution spectra Tolstoy et al. 2001 found that Sculptor's mean metallicity was $<$[Fe/H]$>= -1.5$ with a 0.9 dex metallicity spread. Fornax appears to have a highly variable star formation history spanning from $\sim$ 15 Gyr to 0.5 Gyr ago (e.g. Buonanno et al. 1999). From low resolution spectra Tolstoy et al. 2001 found that Fornax's mean metallicity was $<$[Fe/H]$>= -1.0$ with a 1.0 dex metallicity spread. Carina exhibits a significant variation in star formation rate with time with the bulk of the stars having formed 4-7 Gyr ago (e.g. Hurley-Keller et al. 1998, Dolphin 2002). ¿From low resolution spectra Da Costa 1994 found that Fornax's mean metallicity was $<$[Fe/H]$>= -1.9$ with a 0.1 dex metallicity spread. Leo I exhibits a significant spread in age with the bulk of the stars having formed 2-7 Gyr ago (e.g. Gallart et al. 1999, Dolphin 2002). No low resolution abundance information is available for Leo I. The previous high resolution surveys Shetrone et al. (1998, 2001) sampled Ursa Minor, Draco and Sextans which have star formation histories similar to Sculptor's, dominated by a single old population. Comparing abundances in dSph with extremely different star formation histories, as well as differences from the Galactic halo, allows us to further examine the nucleosynthetic sources for a variety of interesting elements.

2. Observations

Spectra of red giants in four dSph's were obtained at the Very Large Telescope Kueyen at Paranal, Chile, in August 2000 and January 2001 using the Ultraviolet-Visual Echelle

Spectrograph (UVES; Dekker et al. 2000) in visitor mode (see Table 1). The red arm of UVES with CD#3 was centered at 580nm, and with a 1.0" slit, we obtained a resolution ∼40000 (4.4 pixels) over a wavelength range of 480-680nm. The total integration time varied from 2–4 hours (1 hour per exposure), depending on the brightness of the target and the sky conditions. Monodimensional spectra were extracted with the UVES pipeline (Ballester et al. 2000), then continuum normalized and combined with IRAF for a S/N∼30 per pixel.

A variety of elements were detected in the spectra, including Fe, O, Na, Mg, Al, Ca, Sc, Ti, Cr, Ni, Y, Ba, Nd, La and Eu. This allowed for a comprehensive abundance analysis (e.g. Kraft et al. 1992, 1993). Four red giants in clusters of known metallicity (see Table 2) were observed as standard stars to establish the abundance scale. Analysis of these stars allowed us to look for zero point offsets and place our abundances on a standard system.

3. Data Reduction and EW Measurement

Radial velocities for each red giant (see Table 2) were measured from three metal lines (FeI 5083.35, CaI 6122.23, and BaII 6141.73) and two Balmer lines (Hα and Hβ). Heliocentric corrected radial velocities are listed in Table 2. The radial velocities were used to ascertain galaxy membership, and all are in excellent agreement with published values (see the references in Table 2).

Equivalent widths were measured three different ways using the IRAF task *splot*. The first strategy was an integrated flux method (Simpson's Rule), the second was a normal Gaussian fit, the third was using multiple Gaussians for lines that appeared asymmetric or blended with other lines. In the latter cases, the Gaussian FHWM were forced to be the same for all components. When the lines were not asymmetric, EWs were adopted from the integrated flux method, unless a bad pixel in the line profile made the Gaussian fit method preferable. The adopted EW are reported in Tables 3 and 4.

Figure 1 shows a comparison of the EW measured here and those measured for the GC sample from Minniti et al. 1993. There is no systematic trend or offset for the entire sample. The standard deviation of the entire sample is 11.5 mÅ, however the differences are slightly higher at larger EWs which we attribute to a small error that scales with EW. We adopt the errors Minniti et al. use for their EW, 6 mÅ, as the minimum EW measurement error. This uncertainty is shown by the dotted lines in the upper plot of Figure 1. The dashed lines represent a combination of this minimum uncertainty, plus a 10% X EW uncertainty that is added in quadrature. We will use this additional 10% X EW uncertainty later in our error analysis. When each star is examined separately, there do appear to be some systematic differences. For example, our EWs for M55-283 tend to be slightly lower than from Minniti et al. (1993), although still in agreement to within 10%. We attribute these small systematic differences to the choice of continuum normalization.

4. Oscillator Strengths

Most of the oscillator strengths adopted in this work were taken from the Lick-Texas papers (e.g. Kraft et al. 1992 and Sneden et al. 1991) as summarized in Shetrone et al. (1998, 2001), and also from Fulbright (2000). These lines were selected for accurate abundances in metal-poor giants. Because several of the dSph giants in this paper are more metal-rich, than additional lines were added from Edvardsson et al. (1993). In addition, UVES on the VLT has a larger spectral coverage than HIRES on Keck, which allowed us to add more lines. Atomic data for these lines was obtained from the National Institute of Standards and Technology online Atomic Database[2].

4.1. HFS lines

Hyper-fine structure (hfs) plays a role in a number of elements analyzed in this work including Eu, Ba, Cu and Mn. The parameters for the hfs were taken from a number of different references, as noted in Tables 3 and 4. Hfs for Eu were taken from Lawler et al. (2001) but for consistancy we have continued to use oscillator strength from Shetrone et al. (2001). Adopting the Lawler et al. (2001) oscillator strength would shift our Eu abundances up by 0.08 dex. Using the slightly higher solar abundance in Lawler et al. (2001) would reduce this to 0.07 dex offset.

The hfs analysis was examined in all stars, but for weak lines (< 40mÅ) of Cu, La, and Eu the hfs corrections were insignificant. For the star with the strongest Eu line (Fnx 21, 87 mÅ) the hfs correction was 0.23 dex, for all other stars the hfs correction is less than 0.12 dex. For the Ba lines used in this analysis, the hfs corrections and isotope splitting made no significant differences to the abundances, even for the strongest lines. Only for the Mn lines were the hfs corrections significant for all lines (EW $>$ 30 mÅ).

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[2]Available at $http://physics.nist.gov/cgi-bin/AtData/main\_asd.$

5. Analysis

Model atmospheres were taken from the computations of the MARCS code (Gustafsson et al. 1975), and the abundance calculations were performed using the Dec. 19, 2000 version of Sneden's (1973, MOOG) LTE line analysis and spectrum synthesis code. The procedures are identical to those employed in Shetrone et al. (2001) ensuring that the relative abundance and model parameter scales should be similar. In general, a color temperature and metallicity were adopted per program star (discussed below), and the initial temperature was adjusted to minimize the slope in Fe abundance (from Fe I) versus excitation potential. Minimizing the slope between FeI line abundances and their equivalent widths also provided the microturbulent velocity. Following this, the surface gravity was determined by requiring that the abundance of the *ionized* species equal that of the *neutral* species based upon Fe I and Fe II. These steps usually required a few iterations before the parameters converged and were adopted for the abundance analysis. Model atmospheres are from the MARCS grid that are slightly more metal-rich than the actual derived abundances to compensate for the extra electrons that are contributed by alpha-rich metal-poor stars (see Fulbright & Kraft 1999 for more about this methodology). Model atmosphere parameters determined here are listed in Table 5.

In addition, we performed two checks on our model atmospheres analyses. Firstly, the final model temperatures were examined relative to the initial color temperatures derived from the B-V colors. Secondly, the iron (and other) abundances for two stars were also analysed using ATLAS9 model atmospheres (Kurucz 1993) in WIDTH9 with oscillator strengths from the VALD database (Kupka et al. 1999). The two tests are discussed separately below.

The B-V color for each star provided an initial estimate for the stellar parameters. The conversion from color to stellar parameters was made using a calibration based upon the derived parameters for a number of globular cluster stars (Lick-Texas papers; Kraft et al. 1992, 1993, 1995, 1996, Sneden et al. 1991, 1997). Initial estimates were made by assuming a metallicity for each program star based upon their location in the color magnitude diagrams, then these estimates were adjusted for the metallicities actually determined per star. Because the iterative nature of our analysis the final temperatures and surface gravities do not match the initial estimates. On average the temperatures differed little from the initial estimates (ΔT = -3K, σ = 92K) while the final surface gravities are a bit lower than the initial estimates (Δlog g = -0.29 dex, σ = 0.17 dex). Colors were taken from Schweitzer et al. 1995 (for Sculptor), Mateo et al. 1991 (for Fornax), Mateo et al. 1993 (for Carina), and Mateo et al. 1998 (for Leo I). Reddening estimates were taken from Kaluzny et al. 1995 (for Sculptor), Schlegel, Finkbeiner & Davis 1998 (for Fornax), Mould

& Aaronson 1983 (for Carina) and Cardelli, Clayton & Mathis 1989 (for Leo I). A second check of our adopted stellar parameters was performed using the the Alonso temperature scale (see Table 2 in Alonso et al. 1999) and then using that effective temperature and the new Yale-Yonsei isochrones (Yi et al. 2001, Green et al. 1987) to derive surface gravity. The Alonso temperature scale (making the correction in Alonso et al. 2001) and literature B–V colors suggest a slightly cooler temperature than our adopted temperatures (ΔT = +60K, σ = 107 K), however the surface gravities based upon the isochrones is in good agreement with our adopted gravities (Δlog g = -0.07 dex, σ = 0.18 dex). The Tolstoy et al. (in prep) use cousins I while the Alonso use Johnson I. Using Bessell (1986,1990) to convert the colors and converting the E(B–V) to E(V–I) using Dean, Warren & Cousins 1978 we find a similar zero point (ΔT = +51K, σ = 131 K) between our derived temperatures and the Alonso temperature scale. The large dispersion in the between in both V–I and B–V could be due to variable reddening. Inspection of the spectra reveals a factor of two dispersion in EW of the interstellar Na D lines among the Carina sample. As mentioned before we have adopted the spectroscopic temperatures and have only used the photometric temperatures as an initial estimate and a secondary check on our methodology.

Two stars, the cluster star M55-76 and the Sculptor star Scl-459, were checked with ATLAS9/WIDTH9 calculations and VALD atomic data. The abundances for Fe I and Fe II lines are in very good agreement ($\Delta\log(X/\mathrm{H}) \leq 0.1$), and most of the iron line abundance disagreements can be traced primarily to small differences in the oscillator strengths. We note however that the mean differences go in opposite directions for FeI and FeII, so that the ATLAS/WIDTH results do not maintain the iron ionization equilibrium when the MARCS/MOOG parameters are adopted. For example, when FeI=FeII using MARCS/MOOG, then the ATLAS/WIDTH/VALD results are FeI + 0.1 dex = FeII − 0.1 dex, resulting in a 0.2 dex difference between iron from the FeI versus the FeII lines. This will affect the model atmosphere parameters, primarily it will force a higher gravity determination in the ATLAS/WIDTH analysis. While gravity has a very small effect on the FeI abundances (see Table 6), and thus the overall metallicity adopted for that model, it can have a larger effect on the abundances of ionized species and also the O I abundance. This is discussed further below in Section 6.3. Additionally, we stress that the MARCS/MOOG analysis is the most consistent with the published abundances for the globular cluster standard stars and for red giants in other dwarf spheroidal galaxies, thus we consider these the most appropriate for differential comparisons.

6. Error Analysis

We divide our errors into three types: statistical, internal and external. Statistical uncertainties are those errors which can be reduced by using many lines to measure the abundances. The internal errors are those errors based on analysis methodology, such as derivation of T_{eff} or normalization of the continuum. The external errors are those based upon the analysis tools, such as the model atmosphere grid and LTE abundance analysis code.

6.1. Statistical Errors

The statistical errors are determined from the consistency of the abundances derived from each line. Assuming that our derived stellar parameters are approximately correct, the variance in the abundance derived for elements with many lines, such as Fe I, is a measure of our ability to measure consistent EWs and the accuracy of our atomic physics inputs (largely the oscillator strengths and hyperfine structure). Using the Cayrel formalism (1988), we estimate that our random error in EW should be 4mÅ for the dSph stars. The Cayrel formalism simply assumes a line profile affected simply by the S/N (30 in our case), and the number of pixels in the resolution element (4 pixels and R=40,000). For the weakest lines ($\sim$ 10 mÅ), this will introduce an uncertainty of 0.19 dex. For moderately strong lines ($\sim$ 60 mÅ), the uncertainty is 0.03 dex, while for very strong lines ($\sim$ 150 mÅ), its only 0.01 dex. The globular cluster spectra have much higher S/N, thus they will also have smaller EW errors. As mentioned earlier in our comparison of our EW to the Minniti et al. (1993) EW our errors were better represented by a constant with a 10% X EW additional error. Thus we take our actual error to be 4mÅ+ (10% X EW), in the case for the dSph sample).

Since many elemental abundances are derived from only a few lines, then the statistical error is rarely accurately sampled. Thus, we assume that the standard deviation of the Fe I line abundances is typical for most elements. We will refer to this σ as the *average line deviation*. For each element we take the larger of either (a) the standard deviation of the mean of the lines for that element, assuming that there is more than 1 line, (b) the average line deviation divided by the square-root of the number of lines used to determine the abundance for that element, or (c) for elements with only 1 line, then the error based just on EW using the Cayrel formalism plus the (10% X EW) additional error we described earlier.

In Tables 8-11 we have given the abundances and internal statistical error for each element. For Fe I we have listed the number of lines that went into the calculation of the standard deviation of the mean. For the other elements a letter tag is given which represents which method is used. An "S" means that the standard deviation was taken from that element. An "I" means that the average line deviation method was used. An "E" means that the error is derived from the EW error. No uncertainty is given if only an upper limit to the abundance is determined.

6.2. Internal Errors

In Section 5, we computed the difference between our derived stellar parameters and those based upon photometry. From that analysis, we adopt internal uncertainties of ±100K and ±0.2 dex for $T_{\rm eff}$ and log g, respectively. We also estimate that the error in the microturbulent velocity is ±0.2 km s^{-1}. Table 6 lists these effects on the abundances for one star, Car 2, by recomputing the abundances for models with slightly different parameters. We have also listed the effect of choosing a slightly more metal-poor model (i.e., one without the extra metallicity which compensates for the alpha-rich abundance pattern), and the effects of shifting the continuum systematically up such that all of the EW are 4mÅ larger. This continuum error assumes that the line profile width does not grow significantly with EW. This is clearly not true for the very large EW lines but we have made some effort to remove all strong lines from this analysis so to first approximation this is a reasonable assumption. For the globular cluster stars the S/N is much higher and thus we adopt a smaller error in the continuum.

It should be noted that many of these errors are not independent, e.g., a change in the $T_{\rm eff}$ by 100 K introduces a slope in the Fe I line abundances vs. EW plot which is used to determine the microturbulent velocity. A 100 K change in the $T_{\rm eff}$ also upsets the balance of the Fe I vs. Fe II abundances. The last column in Table 6 shows how the abundances would change if we attempted to mediate the effects by recomputing the abundances with a model that was 100K too cool. We adopt this last column as representing the most accurate abundance error based on changes in $T_{\rm eff}$, log g and microturbulence.

To combine the uncertainties per element due to the stellar parameters, continuum placement, and metallicity, we have taken these uncertainties in Table 6 and combined them in quadrature over the entire range of stellar parameters. These *total internal uncertainties* are listed in Table 7.

In this paper, plots of abundances will combine the statistical uncertainty and the internal uncertainties in quadrature to create a single error bar.

6.3. External Errors

External errors due to model atmospheres and analysis methods can be extremely difficult to diagnose and quantify. For example, using spectral indicators to determine the stellar parameters rather than relying on the photometrically derived parameters can shift all of the T_{eff} and/or log g values systematically up or down, which will affect the abundances. The magnitude of the effect on each element can be estimated from Table 6. As a demonstration, if the Alonso temperature scale were adopted, then a shift in temperature by −60 K would have occurred, which shifts all of the [FeI/H] abundances down by 0.06 dex. While this shift is small, it would also have occurred to the globular cluster standard star results. Since the interpretation of the abundances in the dSph galaxies depends on a differential comparison with the globular cluster standards, then these small systematic shifts would not have a significant effect on the final results.

On the other hand, our comparison of MOOG/MARCS abundance results to those from ATLAS/WIDTH/VALD may be more valuable. As an example, the mean abundance results for the Sculptor star Scl-459 from each analysis method are shown in Table 12. As discussed above, the changes to the iron ionization equilibrium would force a slightly higher gravity in an ATLAS analysis. Small changes in gravity would have a negligible effect on the abundances from most of the neutral species, but a more significant effect on the derived abundances for O I and the ionized species. Thus, the absolute O/Fe ratio determined for an individual star could be affected (note that accurate O/Fe abundances is a problem with a large scope in metal-poor stars, and we refer to more specific papers on this problem, e.g., Lambert 2001, Asplund & Garcia Perez 2001). In this paper, the interpretation of the O/Fe ratio is done with respect to standard stars whose analyses are done using the same techniques as the dSph stars. Thus, the *differential* O/Fe abundance ratios are similar whether derived from a MARCS/MOOG analysis or using the ATLAS/WIDTH techniques. The effect of changing the surface gravity on the ionized species is larger. While all of the s-process abundances could be affected by a significant amount (see Table 6, e.g., Ba II/Fe, Eu II/Fe), the comparison of BaII/YII or BaII/EuII will be far less affected. In addition, most of our comparisons of the ionized species abundances, such as [BaII/Fe], should be similarly unaffected if the affect is systematic since our comparisons will be made between our globular cluster giants and our dSph giants.

Other comparisons of abundance results in Table 12 show that there are no further changes between the analyses techniques by greater than 0.1 dex (the hfs of Mn and Cu were not included in the ATLAS/WIDTH analysis). It is also interesting to note that differences in the gf-values can still be important (causing >0.1 dex differences) in the analyses of Al, Sc, and Ti.

No corrections have been made for non-LTE effects on our abundances have have attempted to compare our abundances with similiar LTE analyses to minimize this source of error.

7. Globular Cluster Abundances

Four red giants in three globular clusters were observed as standard stars to check our data reduction and analysis methods. There is excellent agreement in the metallicities derived in this paper with the iron abundances from Minniti et al. (1993), where δ[Fe/H] $= -0.03$ with $\sigma = 0.16$ dex, despite different line sets and oscillator strengths.

The globular cluster stellar abundance ratios are shown in Table 8. The abundances for these globular cluster stars are typical of those published for the halo (c.f., McWilliam 1997) to within the statistical and internal errors, with the exception of Ti. Our Ti abundances fall about 0.15 dex below the typical Ti abundances, e.g., the Ti abundances from Fulbright (2002) who used the same line lists and very similar methodology. Reanalysis of the Shetrone et al. (2001) dSph and globular cluster spectra using only the lines adopted in this analysis revealed only slightly smaller abundances (0.05 dex). Thus, we can not account for this discrepancy, and will limit our discussion of Ti in the dSph stars to differential abundances only.

We find that two, possibly three, of our four globular cluster standard stars show deep mixing. For metal-poor stars (with [Fe/H] = -2.0), deep mixing is detected as a star showing high [Al/Fe] and [Na/Fe], but low [O/Fe] and possibly low [Mg/Fe] (Shetrone 1996). In our sample, M30-D, M55-283, and M68-53 exhibit abundance ratios consistent with this pattern (see Figure 2). Only M55-76 does not appear to have undergone deep mixing. For the Galactic field halo stars, the [O/Fe] and [Mg/Fe] abundances can be grouped with the other even Z elements when there is no evidence of the deep mixing pattern,

8. Dwarf Spheroidal Abundances

In this paper, we discuss the abundance pattern in the dwarf spheroidal stars by element and discuss the nucleosynthesis of these elements in comparison to the Galactic halo. A discussion of the element ratios by galaxy can be found in Tolstoy et al. (2002, hereafter Paper II). Only Carina will be discussed separately here, which may show an alpha-element abundance pattern consistent with theoretical predictions for its bursting star formation history.

8.1. No Deep Mixing in dSph Stars

The surface abundances of Al and Na are very sensitive to deep mixing in red giants. Two (possibly three) of our globular cluster standards show elevated Al in Figure 2. In contrast, all of the dSph stars have halo-like Al/Fe ratios. One object in LeoI (Leo-5) may show a slightly elevated abundance ([AlI/FeI]=+0.42), although this star shows a normal field halo-like Na and O abundances. In fact, all dSph stars show sub-solar [Na/Fe] ratios. Thus, we do not expect any of the dSph stars have undergone deep mixing. As such we will include O and Mg in our discussion of the even Z elements. The Na abundances in our study are consistant with the Stephens (1999) study of halo Na but fall below other studies including our globular cluster sample, Gratton & Sneden 1988 and McWilliam 1995. The Stephens 1999 sample were selected to probe the outer halo and thus may be a slightly different sample than the other halo studies. This will be discussed in a later section.

8.2. Even Z Elements

The theoretical picture for the formation of even-Z elements (O, Mg, Si, Ca, Ti) is in the nucleosynthetic shell-burning during SN II at the end of the life of massive stars. This hypothesis is supported by elemental abundances in halo stars (c.f., McWilliam 1997). It is also important to note that this theoretical picture generally applies to elements formed by alpha-capture, but the results from the halo stars suggest that Ca and Ti also follow this predicted behavior, and Ca and Ti are therefore lumped in with the alpha-elements. We will make a subtle distinction between the true (easy to understand) alpha elements, O, Mg and Si from the heavy even-Z elements Ca and Ti.

In the canonical picture of Galactic halo formation the even-Z elements are produced en masse shortly after a burst of star formation with so little time elapsing that SN Ia have no time to dilute the pure SN II abundance pattern. At later epochs (>1.0 GYR) SN Ia had a chance to contribute. SN Ia are thought to produce little to no O and Mg while they probably are able to produce significant amounts of the iron peak even-Z elements Si, Ca and Ti (see Woosley & Weaver 1995 and Table 3 in Iwamoto et al. 1999). Because of the under production of O and Mg by SN Ia (Iwamoto et al. 1999) the [O/H] and [Mg/H] should remain constant and the [O/Fe] and [Mg/Fe] abundance ratios should decrease with increasing metallicity. Because SN Ia produce some Si, Ca and Ti but less than are produced in SN II, the [Si/H], [Ca/H] and [Ti/H] will rise slightly and the [Si/Fe], [Ca/Fe] and [Ti/Fe] will decrease slightly. In this scenario the even-Z elements slowly transition from a high value to a solar value with increasing metallicity (time).

The yields of the alpha abundances with respect to iron abundances in SN II are mass dependent (Woosley & Weaver 1995) with higher masses producing a larger percentage of alpha elements with respect to iron. If a small star formation event occurs, where relatively few high mass stars are formed, then the most massive SN II may not be present and the ratio of alphas to iron could be altered from the canonical halo SN II abundance pattern. For example, with a Salpeter IMF (Salpeter 1955, and also see Massey 1998 for the IMF for the Local Group) and a small 1000 solar mass star formation event, it is statistically unlikely that stars over 25 solar masses will form. Using the Woosley & Weaver 1995 SN yields such an event will have much lower [O/Fe], [Mg/Fe] and [Si/Fe] abundance ratios (by 0.4 to 0.6 dex) with respect to a much more massive star formation event where many higher mass stars are likely to form. This was also noted by Gibson (1998) in an examination of the upper limit to the IMF. *Thus, a low mass star formation event could produce abundances that are slightly less enhanced than those found in the halo.*

As shown in Figures 3 to 8, even-Z abundance ratios are generally larger than solar in our metal-poor stars, as also seen in the halo. To produce these ratios requires reasonably massive early star formation events. The most metal-poor star in the Sculptor sample (H400) and the more metal-poor star in Leo I (Leo 5) have alpha element ratios consistent with that of the halo (Gratton & Sneden 1988, Gratton & Sneden 1991, Gratton & Sneden 1994, McWilliam et al. 1995, Stephens 1999) indicating only a minor (if any) contribution from SN Ia. In Sculptor (Figures 4 and 7) and LeoI (Figures 5 and 8), the even-Z to iron ratios appear to decrease as Fe increases. These trends are based upon few data points and thus should be viewed carefully. To produce the decline in the even-Z abundance ratios requires either a later epoch of SN Ia contributions, or a later stage of small star formation events which had fewer high mass SN II and thus produced lower even-Z abundance ratios.[3].

In Fornax (Figures 5 and 8), the even-Z ratios appear flat to slightly rising. The average of the [O/Fe], [Mg/Fe] and [Si/Fe] abundance ratios is 0.1 dex ($\sigma 0.1$) which is significantly smaller than that of the halo and our globular cluster sample (excluding the Mg and O for the stars with the deep mixing pattern). Again this can be done either through SN Ia contributions or from later smaller star formation events (lower mass SN II contributions). Fornax has a large spread in ages as indicated from its color-magnitude diagram (c.f., Mateo 1998, Paper II). Thus, one expects to have significant contribution from SN Ia in the younger (more metal-rich) population.

The alpha-element abundance pattern in Carina (Figures 3 and 6) exhibits a large and

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[3]For a review on the star formation histories of the Local Group galaxies, see Mateo 1998. A more detailed discussion of the star formation histories of our four dSph galaxies is included in Paper II.

interesting dispersion that we will address separately below.

8.3. Fe-peak Elements

The Cr, Co, and Ni abundances in the dSph stars are halo-like (Gratton & Sneden 1988, 1991, 1994, Sneden et al. 1991, McWilliam et al. 1995, Stephens 1999) i.e., they remain constant with FeI to within the errors down to [Fe/H]~ -2, as seen in Figure 9. Two stars near [Fe/H]~ -1.1 (LeoI-2 and Scl-H482) may also show slight Ni underabundance. This is interesting because Nissen & Shuster (1997) found a puzzling relationship between Ni and Na (and alpha-elements) in this same metallicity regime in halo stars; a tiny decrease in Ni is accompanied by a moderate decrease in Na (and alpha's) near [Fe/H]~ -1. The Ni underabundance also seems to be related to lower alpha-abundances (and possibly Na) in these two dwarf spheroidal stars.

Sc is also halo-like (i.e. flat near 0.0 dex) for most of our targets, however a few stars (Leo 2, Car 3 and Scl-482) have significant underabundances. We also notice that the Sc abundances plotted in Figure 9 mimic the pattern of the alpha-elements better than that of the iron-group elements. Because the nucleosynthetic origin for Sc is unclear we will not comment further on Sc.

The Zn abundances in our dSph sample are systematically a few dex lower than those found in the Galactic halo (Sneden et al. 1991, Primas et al. 2000) and in our globular cluster sample. This seems to imply that the Zn is behaving differently from the other iron peak elements in ALL of these dSph. This is not entirely surprising since the nucleosynthetic origin of Zn is uncertain with possible origins in SN Ia, SN II and/or AGB stars (Matteucci et al. 1993, Hofman et al. 1996, Umeda & Nomoto 2002).

8.4. Cu & Mn

The formation sites for Cu and Mn are not well known. In halo stars, the Cu and Mn ratios are both less than solar until [Fe/H] ~ -1.0 when they both rise to solar Gratton & Sneden 1988, Gratton 1989, Sneden et al. 1991, McWilliam et al. 1995). The most common interpretation of this pattern is that they are produced in SN Ia (Gratton 1989, Matteucci et al. 1993, Samland 1998, Nakamura et al. 1999). Alternatively, Woosley & Weaver (1995) have suggested a metal-dependent SN II yield, such that at [Fe/H] ~ -1 the metallicity becomes sufficiently high that significant amounts of Cu and Mn can be produced in the SN ejecta (see Timmes et al. 1995 for a chemical evolution model using the Woosley & Weaver

1995 yields).

As shown in Figure 10, our Cu and Mn ratios are consistent with the halo star abundances. They are less than solar over a wide range of low metallicities up to [Fe/H] ~ -1. The similar Cu, Mn, and Fe abundance patterns between the Galactic halo stars and the dSph stars suggest a similar abundance origin. In Figure 10, we also notice that [Cu/alpha] is significantly less than solar and flat for the dSph stars (until [Fe/H]> -1). *This strongly suggests that either SN Ia do not contribute to Cu in the most metal-poor stars, like the alpha-elements, or that any SN Ia contribution to Cu at this metallicity is not significant.* If significant amounts of Cu were being produced in metal-poor SN Ia events, then as Fe increases we would expect Cu/alpha to increase.

ne may question then whether SN Ia products are contributing at all up to [Fe/H]=-1. As discussed in Section 8, either SN Ia are contributing to explain the alpha/Fe ratios, or possibly only small star formation events have occurred (thus lower mass SN II). However, also given the star formation histories for these galaxies, interpreted from their CMDs (see Paper II), it would be surprising if there were no SN Ia contributions until [Fe/H]=-1. All of these galaxies are thought to have had some star formation in the distant past (15 Gyr), with either continuous or bursting star formation at intermediate ages (5-10 Gyr). The intermediate-aged stars can be expected to form from gas enriched in SN Ia products from the earlier generation(s). Thus, we suggest that if Cu is produced in SN Ia, then the yield may be metallicity dependent, with increasing amounts of Cu as metallicity increases. It is also possible that the upturn in Cu/Fe near [Fe/H]=-1 is due to a metallicity dependent SN II yield. This conclusion is not sensitive to the choice of hfs or gf values because it is based on relative abundances within this analysis.

A similar argument can also be made for Mn. Figure 10 shows that Mn/Fe is also flat and halo-like. The halo stars appear to have increasing [Mn/Fe] above [Fe/H]=-1. In the halo, the upturn has been intrepreted as the onset of SN Ia products. We suggest that, like Cu, SN Ia (or even SN II) contributions may be metallicity dependent with very little Mn produced until [Fe/H]=-1.

Omega Cen is another system where [Cu/Fe] is quite low over the same range of ages and metallcities as our dSph stars (Cunha et al. 2002). Unlike the halo stars, [Cu/Fe]~ -0.5 in the star in Omega Cen and does not increase with metallicity. Our dSph results are not inconsistent with this result either, since our Cu/Fe ratios do not increase as quickly as in the halo stars. Cunha et al. similarly conclude that SN Ia contribute very little to the chemical evolution of Cu in the metallicity range of $-2.0 <$ [Fe/H] < -0.8. In contrast, Pancino et al. (2002) found an increasing [Cu/Fe] abundance with increasing metallicity for Omega Cen giants in the metallicity range of $-1.2 <$ [Fe/H] < -0.5. Both of these results could be interpreted as pollution from SN Ia or as metal dependent SN II yields. (A more detailed comparison of the abundance patterns observed in Omega Cen with those found in the dSph is beyond the scope of this paper).

8.5. The First s-process Peak Element, Y

Y samples the first s-process peak, which may have a different source than the heavier (e.g., Ba) s-process elements. In Figure 11, we notice that our most metal-poor stars, have halo-like [Y/Fe] and [Ba/Y] ratios, implying a similar origin or different sources in the same proportion as were found in the halo (e.g., early SN II yields). But, as the metallicity increases, the [Y/Fe] abundance ratios decrease. This representation of the Y abundances is a bit misleading though. The central plot in Figure 11 shows the absolute Y abundances, [Y/H], where it can be seen that Y does actually increases with metallicity for Carina, Leo I and Fornax. The [Y/Fe] ratio decreases though because the Fe abundance is increasing more rapidly than the Y abundance is increasing in these dSph galaxies in comparison to the Galactic halo. For Sculptor, the [Y/H] abundance has a wide dispersion but remains constant over the metallicity range we sample.

A model for the formation of s-process elements in AGB stars by Clayton (1988) suggests that the yields scale with metallicity if the neutron source is the $^{13}C(\alpha,n)^{16}O$ reaction, and this model specifically predicts that [Ba/Y] should increase with metallicity. The bottom panel in Figure 11 shows that [Ba/Y] clearly does increase with metallicity in the dSph stars as predicted. That this pattern is not seen in the halo stars is more peculiar, and suggests a number of possibilities. McWilliam (1997) discussed that the predicted [Ba/Y] relation in the halo may have been erased by the large metallicity dispersion in the halo, i.e., at any given time, the secondary elements are produced from stars with a variety of metallicities and thus yields. This interpretation predicts that the rising [Ba/Y] ratio in the dSph is caused by chemical evolution occurring over a longer period of time (in comparison to the halo) and thus AGB stars of a narrower range (in comparison to the halo) in metallcity are contributing to the ISM. Another option might be that that the seed for the first s-process peak (C?) is underabundant in the dSph galaxies. Low resolution spectra of several dSph's show high carbon abundances though with respect to Galactic globular clusters of similar metallicities (Kinman et al. 1980, Smith & Dopita 1983, Smith 1984, Bell 1985). A third option, if we forgo Clayton's model, could be that there is a source of Y in the Galactic Halo that is not present in the higher metallicity dSph stars. Since most studies of SN II yields do not include the first s-process peak then we cannot compare this hypothesis with any models. The first option above is the most consistent with the overall abundance patterns.

The Y enrichment in the metal-rich Fornax star, Fnx-21, is consistent with other s-process enrichments in this star (discussed below).

8.6. s-process and r-process Elements

In the Sun, Eu is largely an r-process element, 95% (Burris et al. 2000). The site of the r-process has been suggested to be low mass SN II (Mathews et al. 1992), but the site for the r-process is still a matter of debate (e.g. Wallerstein et al. 1997, Tsujimoto & Shigeyama 2001, Qian 2002). However, most of these models share a common prediction: SN II are the source of the r-process. Thus, [Eu/H] should rise whenever SN II contribute to the ISM, and only when SN Ia and AGB stars contribute to the ISM should [Eu/H] remain constant and the [Eu/Fe] ratio decline. The Eu abundances are plotted in Figure 12. In Leo I and Fornax the [Eu/H] abundance increases with metallicity as expected if there has been some ongoing star formation with SN II contributing to the ISM. A similar slope is also seen in the Galactic halo stars (Gratton & Sneden 1991, Gratton & Sneden 1994, McWilliam et al. 1995, Burris et al. 2000). Thus we predict a burst of star formation between [Fe/H] -1.5 to -1.1 for Leo I and -1.5 to -1.2 for Fornax. These predictions are provisional given the few number of points and the large errorbars. On the other hand, the Sculptor [Eu/H] abundances are relatively flat over the entire metallicity range sampled which implies little to no later contribution of SN II to the ISM. Thus for Sculptor, we predict that only a single burst occurred or that the material from SN II was completely lost from the galaxy in any later bursts. The Carina abundances will be discussed separately below.

Oddly, the most metal-poor star in Sculptor, H-400, has a larger [Eu/H] abundance than Galactic halo stars of similar metallicity. The top panel of Figure 12 shows that this star has [Eu/Fe] = +1.0, and, as we will show later, an r-process dominated abundance pattern. This type of super r-process rich abundance pattern has been seen among Galactic halo stars (McWilliam et al. 1995) and attributed to inhomogenous mixing of the SN II yields (McWilliam et al. 1997), i.e., the star forms after the local ISM is contaminated by a nearby r-process rich SN II and before the ISM is well mixed. However, all of these Galactic r-process rich stars are more metal-poor than H-400. This high [Eu/Fe] abundance could be due a wide dispersion in [Eu/H] at [Fe/H] = -2.0 and we have only sampled the upper end of that distribution.

A comparison of s&r-process elements to Eu (a largely r-process element) allows us to examine the contributions to the abundances from AGB stars. The s-process/r-process ratios are shown in Figure 13. The pure r-process contributions to these elements from Burris et al. (2000) are shown by the dotted lines, while the solid line shows the pure r-process contributions from Arlandini et al. (1999). The Burris et al. contributions are calculated using the "classical approach" which models the neutron flux of an AGB star with a simple analytical model. The Arlandini et al. values come from a new generation of AGB evolutionary models. Of course comparison to these solar system fractions requires our abundances to be on an absolute scale and introduces many additional concerns. The r-process fractions should be considered free parameters able to slide up or down within our abundance scale. It is important to stress that La and Ba are often called s-process elements based upon the fraction of these elements that were produced by the s-process **in the Sun**. However, in the early Universe and apparently in the most metal-poor stars in these dSph we expect that all the heavy elements present have their origins in the r-process since AGB stars would not have had time to evolve and contribute to the ISM (Truran 1981). Indeed, in our most metal-poor stars, the Ba, Nd and La abundances are consistent with primarily r-process contributions. Note that in the Sun, La and Ba are mostly s-process elements (85% and 75% respectively from Burris et al. (2000) while Nd is thought to be (roughly) half produced in the s-process and half in the r-process. Nd alone does not actually constrain the abundance contributions significantly.

The [Ba/Eu] and [La/Eu] ratios in Sculptor, Fornax and Carina clearly increase with metallicity, as in the halo stars. This suggests that some level of star formation must have continued after any initial, early epoch star burst so that subsequently more metal-rich objects could be contaminated from the early metal-poor AGB stars. Of course, this contamination time scale must be *greater* than the life time of the AGB stars (~ 1 Gyr). The seemingly flat [Ba/Eu] and [La/Eu] ratios in Leo I suggest that the contribution from AGB stars must have been fairly small (from metallicity [Fe/H] $= -1.5$ to [Fe/H] $= -1.1$). Thus the timescales between these two epochs should have been fairly short. A short timescale between these two epochs would imply that there should be little SN Ia contribution during this period and thus any decline in the even-Z elements would be due to small star formation events and thus few high mass SN II to produce alpha elements. More stellar abundances in this metallicity range would help to confirm this suggestion since with only two stars cannot rule out a small slope in the [Ba/Eu] and [La/Eu] ratios.

The metal-rich star in Fornax, Fnx-21, shows remarkable enrichment in all s-process elements (and possibly Eu), often greater than the enrichments in the Galactic halo stars and clearly shows a super-solar s/r ratio. The most likely possibility is that this star underwent mass transfer in a binary system with an evolved AGB star. However, with such a small sample of stars we cannot rule out the possibility that the most metal-rich stars in Fornax have had a very large s-process enrichment from AGB stars in comparison to the total number of r-process SN events. However, this second hypothesis seems to contradict the slightly enhanced alpha/Fe ratio and an increasing [Eu/H] abundance with increasing metallicity which imply continued contribution from SN II. Only analyses of additional metal-rich stars in Fornax will be able to distinguish between these two possibilities.

8.7. Carina's Abundance Pattern

Carina has a bursting star formation history as determined from its CMD (Hernandez et al. 2000, Hurley-Keller, Mateo & Nemec 1998, Smecker-Hane et al. 1994, Mighell 1990). One might expect to see this signature in the alpha-element/Fe ratios. After EACH burst, the alpha-element ratio increases rapidly (because of the rapid influx of alpha rich SN II material; e.g. Gilmore & Wyse 1991), followed by a slow decline as Fe is produced by the SN Ia supernovae. Of course, to sample this pattern would require some low level of star formation between each burst. Also, this assumes a fully sampled IMF, which may not occur (statistically) in very low mass star formation events.

In Carina, we may see this pattern for the first time in any galactic system[4]. Our most metal-poor star (Car-10, [Fe/H]=-1.94) has slightly enhanced [α/Fe] ratio, but the next most metal-poor star (Car-3, [Fe/H]=-1.65) has quite a low [α/Fe]. In addition the [α/H] ratio of Car-10 and Car-3 are nearly the same which implies that the increase in iron peak elements was not accompanied by any detectable increase in the alpha elements, as is expected from SN Ia. The remaining three objects return to high [α/Fe] (perhaps even higher than Car-10) as predicted if a burst of star formation followed that polluted the interstellar medium with alpha-elements. If this interpretation is correct the burst must have happened between [Fe/H]=-1.65 and [Fe/H]=-1.60, according to our iron abundances; this is the metallicity range predicted $\sim$7 Gyr ago when a burst lasting 2-4 Gyr is predicted by Hurley-Keller et al. (1998) and Hernadez et al. (2000). Further discussions of ages and burst populations are discussed in Paper II).

The pattern repeats in all of the alpha-elements, strongly suggesting that this is not a problem with a particular set of absorption lines (e.g., that Car-3 and its analysis is NOT unusual). We also strongly suggest that this is not a pattern brought on by atmospheric parameter uncertainties since the Fe abundances and temperatures are quite typical. The only distinction is that Car-3 has a very low gravity determination, however most of the alpha-element ratios are NOT sensitive to gravity (e.g., Mg, Si, Ca, Ti, see Table 6) and

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[4]Very recent analyses of red giants in LMC clusters may also show the alpha/Fe ratios predicted from bursting star formation history models, Hill (2002).

still show this pattern.

In addition to the alpha-abundance pattern in the five Carina stars, we find supportive evidence that their chemical abundances are related to the star formation history in the s&r-process ratios as well. The Ba, La, Nd, and Eu abundances are all similar to primarily r-process in the most metal-poor star (Car-10, [Fe/H]=−1.94). In the next star (Car-3, [Fe/H]=−1.65), the Ba/Eu, La/Eu, and Nd/Eu appear to be very slightly larger, suggestive of some small s-process enrichment; the SFH by Hurley-Keller et al. 1998 suggests a 3 Gyr hiatus between the first and second bursts of star formation, which is sufficient time for AGB stars to contribute some s-process fraction. The next two stars, with [Fe/H]=−1.6, show a significant increase in La/Eu, and also slight increases in Ba/Eu and Nd/Eu. This suggests further AGB contributions. The increase in their alpha elements implies SN II contributions, which could also provide the r-process elements, and drive down the ratio of s-process to r-process abundances, but we do not see this. Possibly very little r-process elements were formed or were incorporated into the ISM when these stars formed, or the AGB contributions were simply more significant. It is important to point out that we are not predicting that Car-3 was formed in the second burst. Car-3 could have been formed in an intermediate star formation event some considerable time before the second burst and thus further AGB contamination could have occurred.

One difficulty in the interpretation of the chemical evolution of Carina as a burst pattern is the flat (or even declining) [Eu/H] abundances, see Figure 12. If we expect significant SN II between the Car-3 and the [Fe/H]= −1.6 Carina stars then we might expect a rise in the [Eu/H] abundance since Eu (as a primarily r-process element) is thought to be produced in SN II. One possible explanation for this contradiction is that the mass range of SN that produce most of the Eu at this metallicity is narrow enough that a low mass IMF would restrict the number of these events. Another possibility is that some of the subsequent r-process material has been lost from the galaxy (blow-out?). Since we detect a factor of two increase in the even-Z abundance the blow-out would have to be very selective. But a final possibility is simply that we have underestimated our errors for the Eu abundance based on this single very weak line and cannot detect a subtle increase in Eu that may be present.

Figure 14 is an alternative way to view the entire chemical evolutionary history for Carina. Figure 14 shows the abundance pattern for Car-10, Car-12 and Car-3. The abundance pattern has been normalized to Mg for the light elements and normalized to Eu for the heavy elements. The top panel shows the solar system abundance pattern as a solid line and the dotted line represents the abundance pattern implied by SN IIL SN from Qian and Wasserburg (2002) while the dashed line represents the the r-process abundance pattern from Arlandini et al. (1999). The solid line and the dotted line deviate furthest apart in the iron peak, elements Cr - Ni. We show the abundance pattern of three Carina stars, filled squares representing Car 10 (our most metal-poor Carina giant), crosses representing Car 3 (the Carina giant with the extremely low alpha to iron abundance ratio), and open squares representing Car 12 (our most metal-rich Carina giant). Among the iron peak elements the Car 3 abundances stand out as anomalous, while the Car 12 and Car 10 abundances lay between the solar and SN IIL SN abundance patterns. Among the heavy elements there appears to be a spread in the abundance pattern with Car 10 fitting the Arlandini et al. (1999) pure r-process abundance pattern and Car 12 being closest to a solar abundance pattern. Because of the large dynamic range in the top panel of Figure 14 a comparison between the different abundance patterns is difficult.

The bottom panel for Figure 14 shows the same abundance pattern but with the average globular cluster abundance removed. Since we only have a single globular cluster star without the deep mixing abundance pattern we have adopted the Mg and O abundances from that star (M55-76) and have excluded Na and Al. The points in the bottom panel of Figure 14 are the same as those given in the top with the addition of open circles which represent the solar abundance pattern. The elements below atomic number 20, ie. O, Mg, Si are similar to that of the globular cluster but the iron peak elements, ie. atomic number 21-30, are clearly overabundant. The X's (Car-3) exhibit the highest overabundance in the iron peak. As mentioned before we interpret this to be a due to a long period of SN Ia contamination before a later burst which brings the peak back down (or the alpha elements back up). The fact that the most metal-poor Carina star (Car-10) shows an overabundance of iron peak elements does not necessarily mean that SN Ia have contributed to its abundance pattern since as we have mentioned previously a low mass star formation event can produce a low alpha, with respect to the iron peak, abundance pattern. The heavy elements also show a clear evolution toward the solar abundance distribution (the open symbol Car-12 is the most metal-rich in the Car sample and shows the most solar like heavy element abundance distribution). We interpret this to mean that significant time has passed between the formation of each of these dSph stars, i.e., to allow subsequent AGB contamination.

If this burst-like abundance pattern can be supported with other stars in Carina in this metallicity range (near [Fe/H]=-1.6), then this would be the first proof of the theoretical bursting galaxy chemical enrichment models.

9. Discussion

The underabundance of the alpha elements (with respect to globular cluster stars) found at [Fe/H]$= -1.5$ can be interpreted in two ways; either as the onset of SN Ia at lower metallcities than is found in the halo, or as a small star formation event where there are very few massive stars (the ones that produce the alpha elements). Since the IMF is similar in nearly every environment in which it is studied (e.g., Magellanic Clouds and Galactic clusters, Massey 2003), then usually the alpha-element ratios is interpreted in terms of the onset of SN Ia, but the effect of the absence of many massive stars in a small star formation event should not be ignored. However, for Fornax and Carina where a large spread in ages is expected (see Mateo 1998, Hernandez et al. 2000, Hurley-Keller, Mateo & Nemec 1998, Smecker-Hane et al. 1994, Mighell 1990, and Paper II), then SN Ia contamination should be expected at higher metallicities.

We also note that, if the iron-peak enhancements (as seen in Figure 14) are due to SN Ia, over the metallicity range $-2 <$ [Fe/H]< -1, and yet the [Mn/Fe] and [Cu/Fe] remain flat, then SN Ia can not be the cause of the upturn in Mn and Cu seen among the Galactic halo stars. This is also supported by the very low [Cu/alpha] ratios shown in Figure 10. As discussed in Section 8.4, we suggest that a metallicity-dependent SN yield (e.g., SN II, Timmes et al. 1995), may be the formation site for Cu and Mn in metal-poor stars.

A similar type of argument can also be made for the source of the first s-process peak in metal-poor stars. Since the timescales for SN Ia and AGB contamination are similar, and the slopes of [Y/H] vs [Fe/H] are different between the Galactic halo stars and the dSph stars, then the source for Y in metal-poor stars is not SN Ia nor AGB stars. *It must come from another source, such as SN II (again, possibly a metallicity-dependence).* The large [Ba/Y] ratio seen in the dSph stars with [Fe/H] > -1.6 (see Figure 13) might be due to Ba (but not Y) being enhanced by the s-process. The fact that the most metal-rich star in Fornax, Fnx-21, has Ba/Y that is halo-like is due to increased Y (also seen in Figure 13), mostly likely because Y has been enhanced by a greater factor than Ba (since Ba, and La, are also enhanced in this star) from more metal-rich AGB stars. If Zn also has a small component that is linked to the first s-process elements then the slight underabundance of Zn might be linked to the underabundance of Y.

9.1. DSph Abundances and the Galactic Halo

Several lines of evidence suggest that the Galactic halo is, at least partially, composed of accreted dSph galaxies. These include the current assimilation of the Sgr dwarf

(Ibata et al. 1997, Dohm-Palmer et al. 2000, Newberg et al. 2002), and possibly Omega Cen (Majewski et al. 2000, assuming that it is a stripped dSph). The abundances presented here for the metal-poor stars in four dSph's show a strong iron peak signature (regardless of the origin) or viewed differently as low alpha to iron ratio with respect to Galactic halo stars. Since the halo's metallicity distribution peaks near [Fe/H] = -1.8 and those stars show a higher alpha to iron ratio than the dSph stars (see the Figures 3-8 in this work and Figure 12 in Fulbright 2002), clearly a large percentage of the halo can not have be produced from dSph similar to those analyzed here or we would see a many stars with a strong iron peak abundance pattern in the halo. Fulbright (2002) found that less than 10% of the local metal-poor ([Fe/H] < -1.2) stars sample have alpha to iron abundance ratios similar to those found in the dSph sampled in this work and SCS01. However, by subdividing his sample by total space velocity, the highest space velocity stars have systematically lower alpha to iron abundance ratios. Stephens' (1999) sample was kinematically selected to probe the outer halo by looking for high velocity local stars. This sample also exhibits low [Na/Fe] ratios and low even-Z to iron ratios (with respect to the other halo samples). At the same metallicities as the Stephens (1999) sample, our dSph samples have low [Na/Fe] and even lower low even-Z to iron ratios. Perhaps the disrupted dSph were similar to those studied in this work contribute to the the high space velocity tail Galactic halo.

Nissen & Schuster (1997) conducted a detailed abundance analysis of a nearby sample of disk and halo stars with similar metallicities to study the disk-halo transition. Their sample was chosen to get an equal number of disk and halo stars as defined by the stars stellar rotation. Of their 13 chosen halo stars, 8 show an unusual abundance pattern: low alpha element to iron ratio, low [Ni/Fe] abundances and low [Na/Fe] abundances. These odd halo stars also exhibited larger R_{max} and z_{max} orbital parameters than the other halo stars sampled. Nissen & Schuster (1997) suggest that these anomalous stars may have their origins in disrupted dSph. The dSph stars in our sample at a similar metallicity [Fe/H] $= -1.0$ also exhibit sub-solar [Na/Fe] and [Ni/Fe], and low even-Z to iron abundances. This seems to lend support to the idea put forward by Nissen & Schuster (1997) that a large fraction ($> 50\%$) of the metal-rich halo may have their origin in disrupted dSph like those studied in this work.

This still leaves the question of the origin of the metal-poor halo though, and the fraction of the metal-poor halo that formed through monolithic collapse versus accretion of dSph galaxies. We note that we have examined the [alpha/Fe] ratios in a subset of the dSph stars, that is those with the oldest ages ($\sim$15 Gyr, from Paper II). On average, [alpha/Fe] $\sim +0.15$ with a range from solar to $+0.4$. This average is still lower than the metal-poor (presumably old) halo stars, yet the range does overlap. It is likely that some fraction of the old, metal-poor halo is composed of disrupted dSphs like those examined here, but we continue to agree with SCS01 that the dSphs cannot account for the majority.

9.2. Connection to other dSph Galaxies

There are not a large number of publications with high resolution detailed abundance analyses of dSph stars. Bonifacio et al. (2000) and Smecker-Hane & McMilliam (2002) have samples of stars in the Sagittarius dSph. Shetrone et al. (1998) analyzed 4 giants in the Draco dSph and these results were incorporated into SCS to yield a sample of 6 giants in Draco, 6 giants in Ursa Minor, and 5 giants in Sextans.

The SCS sample should be the most straight forward to compare with this work since many of the methods are the same. The population sampled in Draco, Ursa Minor and Sextans contains more very metal-poor ([Fe/H] < -2) so we shall restrict ourselves to comparisons between $-2 <$ [Fe/H] < -1. The overall abundance distribution differences could be better addressed in a low resolution abundance population paper. In this restricted metallicity range the Draco, Ursa Minor and Sextans samples have very similar abundance patterns to the dSph abundance patterns of Sculptor, Fornax, Leo I and Carina. This includes under abundant alpha to iron abundance ratios with respect to the halo, a slightly lower [Zn/Fe] than found in the halo, a low [Y/Fe] at the slightly higher metallicities. The one exception to the similarities is the evolution from low s-process to r-process ratios to high s-process to r-process ratios seen in Fornax, Carina and Sculptor and not in Leo, Draco, and Ursa Minor (unfortunately no Eu abundances were determined by SCS for Sextans). This single difference is likely due to a star formation history which does not seem to be linked in any obvious fashion to galaxy mass since Fornax has the largest mass out of this sample and Carina and Sculptor are some of the least massive. Despite this lingering question it is comforting that all of these dSph have very similar intermediate chemical evolutionary histories.

Combining the Sagittarius dSph samples into a single picture (Bonifacio et al. 2000, Smecker-Hane & McMilliam 2002) reveals a galaxy that seems to be intermediate between the Galactic halo and the dSphs in this paper. The metal-poor stars ([Fe/H] ~ -1.5) in this paper and SCS exhibit slightly enhanced [alpha/Fe] (defined as the average of [Si/Fe], [Ca/Fe] and [Ti/Fe]) but less than the ratios seen in the Galactic halo. For the metal-poor stars in the Sagittarius dSph, [alpha/Fe] are slightly higher. But, as mentioned earlier, the [Ca/Fe] and particularly [Ti/Fe] abundances may not be good indicators of the relative contribution of SN II to SN Ia since some models of both types of SN produce both Si, Ca and Ti in reasonably similar amounts (see Woosley & Weaver 1995 and Table 3 in Iwamoto et al. 1999).

It should be noted that one of the three Smecker-Hane & McWilliam metal-poor stars exhibits a deep mixing abundance pattern. However, no metal-poor dSph stars in SCS or this work show a deep mixing abundance pattern.

The metal-rich stars in the Sagittarius dSph ([Fe/H] ~ -0.5) exhibit solar like [alpha/Fe] and slightly enhanced s-process to r-process ratios of heavy elements. These metal-rich stars also exhibit a large deficiency of Al, Na, Ni and Y. Again, the metal-rich stars share some similarities to the Nissen & Shuster (1997) anomalous stars. There is little overlap between the metal-rich stars in the Sagittarius dSph and the other published dSph abundances though; only the one star in, Fnx-21, is as metal-rich, but it may be an anomalous s-process rich mass transfer star (see above). Comparisons between the Sagittarius dSph and the other dSph will have to wait until larger surveys of the metal-poor Sagittarius dSph and the metal-rich other dSph are conducted.

10. Summary

Certain abundance patterns appear to be very similar between the four dwarf spheroidal galaxies studied here (the Sculptor, Fornax, Leo I, and Carina dwarf spheriodals) and the others examined in the literature (the Ursa Minor, Draco, Sextants, and Sagittarius dwarf spheriodals). These include;

1. Galactic halo-like abundances for the iron-group elements, in particular [Sc/Fe], [Cr/Fe], [Co/Fe], and [Ni/Fe]. In addition, [Mn/Fe] is halo-like in all the dSph stars.

2. The most metal-poor dSph stars, with [Fe/H] < -1, show halo-like s&r-process abundance patterns and [Cu/Fe] abundances. The only exception is the first peak s-process element, Y, where [Y/Fe] is lower than in the halo.

3. The most metal-poor dSph stars, with [Fe/H] < -1, show lower [Zn/Fe] abundance ratios than the Galactic halo stars.

4. None of the stars in the dSphs show the deep mixing abundance pattern (a possible exception may be one star in Sagittarius). For example, all of the dSph stars with [Fe/H] < -1 show a very low Na abundance, with [Na/Fe] ~ -0.4.

The alpha-element abundance patterns are not similar between the dSphs though. The [alpha/Fe] ratio can vary from galaxy to galaxy and can vary with metallicity in an individual galaxy. Specifically, Carina shows a wide dispersion in the [alpha/Fe] ratios at a given metallicity, which we interpret in terms of its bursting star formation history. Sculptor and Leo I show a slightly declining alpha abundance pattern with increasing metallicity, as do Sextants, Ursa Minor, and Sagittarius. Fornax and Draco show a roughly constant alpha abundance over the metallicites sampled. The alpha/Fe ratios in the dSph stars continue to be lower than seen in Galactic halo stars of similar metallicity, thus we remain in agreement with Shetrone et al. (2001) that the majority of the Galactic halo cannot have formed from disrupted dSph systems. However, similarities in the [Ni/Fe] and [Na/Fe] abundances with high velocity halo stars from Nissen & Schuster (1997) may suggest that as much as 50% of the metal-*rich* halo is comprised of dSph stars.

Despite the generally halo-like s&r-process abundances in the metal-poor stars (above), not every dSph exhibits the same evolution in the s&r-process abundance pattern. Carina, Sculptor and Fornax show a rise in the s/r-process ratio with increasing metallicity, evolving from a pure r-process ratio to a solar-like s&r-process ratio. On the other hand, Leo I, Draco, and Ursa Minor appears to show an r-process dominated ratio over the range in metallicities sampled. Again, we attribute this to differences in the star formation histories of these galaxies.

The dSph abundances place new constraints on nucleosynthetic origins of several elements. We find that [Cu/Fe] and [Cu/alpha] are flat over a large range in metallicity in all of the dSph stars. We take these abundance ratios in combination with the known age spread in several of the dSphs as evidence for a metallicity dependent SN (Ia or II) yield for Cu. The same is found for Mn. Also, we attribute differences in the evolution of [Y/Fe] in the dSph stars versus the halo stars to a very weak AGB or SN Ia yield of Y (especially compared to Ba). That a lower and flatter Ba/Y ratio is seen in the halo is due to the pattern being erased by the large metallicity dispersion in the halo (as described by McWilliam 1997). If Zn also has a small component that is linked to the production of the first s-process elements, then the slight underabundance of Zn might be linked to the underabundances in Y.

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Fig. 1.— A comparison the EW from this work and Minniti et al. 1993. The triangles represent M30 D lines, the squares represent M55 283 lines, the crosses represent M55 76 and the circles represent M68 53 lines. The solid line is the 45 degree line. The dotted line is offset from the 45 degree line by an error of 6 mÅ. The dashed line represents a 10% error convolved with the 6mÅerror.

Fig. 2.— Na and Al abundances for our sample: Carina (red squares), the Sculptor (blue circles), Fornax (green triangles) Leo I (magenta pentagons), and the globular cluster abundances (large open squares). The small symbols are taken from the literature to represent the disk, and halo populations: Edvardsson et al. 1993 (small circles), Nissen & Schuster 1997 (small stars), Stephens 1999 (small pentagons), Gratton & Sneden 1988 (small squares), and McWilliam 1995 (small triangles). The errorbars presented here are the systematic errors in Tables 8-11 and the internal errors from Table 7 added in quadrature.

Fig. 3.— Carina [O/Fe], [Mg/Fe] and [Si/Fe] abundances (red squares) are plotted against metallicity. The symbol types are the same as Figure 2 with the addition of Gratton & Sneden 1991 and Gratton & Sneden 1994 (small squares). The errorbars presented here are the systematic errors in Tables 8-11 and the internal errors from Table 7 added in quadrature.

Fig. 4.— Sculptor [O/Fe], [Mg/Fe] and [Si/Fe] abundances (blue circles) are plotted against metallicity. The symbol types are the same as Figure 3. The errorbars presented here are the systematic errors in Tables 8-11 and the internal errors from Table 7 added in quadrature.

Fig. 5.— Fornax (green triangles) and Leo (magenta pentagons) [O/Fe], [Mg/Fe] and [Si/Fe] abundances are plotted against metallicity. The symbol types are the same as Figure 3. The errorbars presented here are the systematic errors in Tables 8-11 and the internal errors from Table 7 added in quadrature.

Fig. 6.— Carina (red squares) [Ca/Fe], [TiI/Fe] and [TiII/Fe] abundances are plotted against metallicity. The symbol types are the same as Figure 3. The errorbars presented here are the systematic errors in Tables 8-11 and the internal errors from Table 7 added in quadrature.

Fig. 7.— Sculptor (blue circles) [Ca/Fe], [TiI/Fe] and [TiII/Fe] abundances are plotted against metallicity. The symbol types are the same as Figure 3. The errorbars presented here are the systematic errors in Tables 8-11 and the internal errors from Table 7 added in quadrature.

Fig. 8.— Fornax (green triangles) and Leo (magenta pentagons) [Ca/Fe], [TiI/Fe] and [TiII/Fe] abundances are plotted against metallicity. The symbol types are the same as

Figure 3. The errorbars presented here are the systematic errors in Tables 8-11 and the internal errors from Table 7 added in quadrature.

Fig. 9.— Iron peak abundances for our sample: Carina (red squares), the Sculptor (blue circles), Fornax (green triangles) Leo I (magenta pentagons), and the globular cluster abundances (large open squares). The symbol small types are the same as Figure 3 with the addition of Sneden et al. 1991 (small squares) and Primas et al. 2000 (crosses). The errorbars presented here are the systematic errors in Tables 8-11 and the internal errors from Table 7 added in quadrature.

Fig. 10.— Mn and Cu abundances for our sample: Carina (red squares), the Sculptor (blue circles), Fornax (green triangles) Leo I (magenta pentagons), and the globular cluster abundances (large open squares). The small symbols are taken from the literature to represent the disk, and halo populations: Gratton 1989 (small squares), McWilliam 1995 (small triangles) Gratton & Sneden 1988 (small squares), Sneden et al. 1991 (small squares) and Primas et al. 2000 (crosses). α is defined as the average of the Mg and Ca abundances. The errorbars presented here are the systematic errors in Tables 8-11 and the internal errors from Table 7 added in quadrature.

Fig. 11.— The Y and Ba abundances for our sample: Carina (red squares), the Sculptor (blue circles), Fornax (green triangles) Leo I (magenta pentagons), and the globular cluster abundances (large open squares). The symbol small types are the same as Figure 10 with the substitution of Burris et al. 2000 (small crosses). The errorbars presented here are the systematic errors in Tables 8-11 and the internal errors from Table 7 added in quadrature.

Fig. 12.— The Eu abundances for our sample: Carina (red squares), the Sculptor (blue circles), Fornax (green triangles) Leo I (magenta pentagons), and the globular cluster abundances (large open squares). The small symbol types are the same as Figure 9 with the addition of Eu for the Edvardsson et al. 1993 coming from Koch & Edvardsson 2002 and the small crosses representing data from Burris et al. 2000. The errorbars presented here are the systematic errors in Tables 8-11 and the internal errors from Table 7 added in quadrature.

Fig. 13.— The s&r-process element ratios for our sample: Carina (red squares), the Sculptor (blue circles), Fornax (green triangles) Leo I (magenta pentagons), and the globular cluster abundances (large open squares). The small symbol types are the same as Figure 10 with the addition of Eu for the Edvardsson et al. 1993 coming from Koch & Edvardsson 2002 and the small crosses representing data from Burris et al. 2000. The dotted line represents the pure r-process abundance ratios from Burris et al. 2000. The solid line represents the pure r-process abundance ratios from Arlandini et al. 1999. The errorbars presented here are the systematic errors in Tables 8-11 and the internal errors from Table 7 added in quadrature.

Fig. 14.— The top panel shows the abundance patterns for Car 10 (red filled squares), Car 12 (red open squares) and Car3 (red crosses) normalized to the Mg abundance, for the light elements and Eu for the heavy elements. The solid line is solar abundance pattern, the dotted line is the predicted SN IIL abundance pattern from Qian & Wasserburg (2002) and the dashed line is the pure r-process abundance pattern from Arlandini et al. (1999). The bottom panel shows the residual abundances pattern for the same three stars after subtracting off our observed globular cluster abundance pattern. The open circles represent the solar system abundances. The Na and Al abundances are excluded in the bottom panel. The errorbars presented here are the systematic errors in Tables 8-11 and the internal errors from Table 7 added in quadrature.

Table 1. Observations

Date	Begin UT	Object	Exp (secs)	Airmass	DIMM[1] arcsec	Comments
16Aug2000	04:24	Scl-H461	3600	1.36	0.92	
16Aug2000	05:26		3600	1.15	0.98	
16Aug2000	06:29		3600	1.05	0.66	
16Aug2000	07:34	Scl-H400	1945	1.02	0.46	tracking
16Aug2000	09:03		3600	1.09	0.55	
17Aug2000	04:53		3600	1.23	0.58	
17Aug2000	05:56		3600	1.09	0.56	
18Aug2000	04:18	Scl-H479	3600	1.35	0.54	
18Aug2000	05:20		3600	1.15	0.53	
19Aug2000	03:24	Scl-H482	1800	1.80	0.45	
19Aug2000	03:56		1800	1.50	0.44	
19Aug2000	04:30		3600	1.28	0.45	
19Aug2000	05:35	Scl-H459	3600	1.11	0.32	
19Aug2000	06:37		3402	1.03	0.29	tracking
19Aug2000	09:06		3600	1.11	0.85	
17Aug2000	07:04	Fnx-M22	2068	1.17	0.82	C-star
17Aug2000	08:58	Fnx-M12	1273	1.02	0.70	tracking
18Aug2000	06:26		3600	1.24	0.53	
18Aug2000	07:28		4500	1.09	0.47	
18Aug2000	08:44		1890	1.02	0.43	tracking
18Aug2000	09:29		1800	1.02	0.43	
19Aug2000	07:58	Fnx-M25	3600	1.05	0.57	
20Aug2000	07:45		3600	1.06	0.85	
20Aug2000	08:47		3600	1.02	1.08	
21Aug2000	09:16		3200	1.02	0.84	
20Aug2000	09:51	Fnx-M21	1200	1.03	0.99	
22Aug2000	07:09		3200	1.10	0.74	
22Aug2000	08:10		3600	1.03	0.89	
22Aug2000	09:12		2382	1.02	0.79	tracking
22Aug2000	09:55		572	1.03	0.80	twilight
17Aug2000	04:15	M30-starD	600	1.00	0.49	
17Aug2000	04:34	M55-star76	300	1.12	0.42	
17Aug2000	04:40		300	1.13	0.49	
18Aug2000	23:17	M55-star283	300	1.35	0.46	
18Aug2000	23:23		300	1.33	0.48	
17Jan2001	02:07	Car-12	3600	1.15	0.42	
17Jan2001	03:11		3600	1.12	0.47	
17Jan2001	04:17	Car-2	3600	1.16	0.61	
17Jan2001	05:18		3600	1.25	0.62	
18Jan2001	01:31	Car-4	3600	1.18	... [2]	
18Jan2001	02:33		3600	1.13	... [2]	
18Jan2001	03:39	Car-10	3600	1.13	... [2]	
18Jan2001	04:41		3600	1.19	0.46	
19Jan2001	00:19	Car-3	1200	1.37	0.76	
19Jan2001	02:33		3600	1.13	0.76	
19Jan2001	03:34		2700	1.12	0.67	
17Jan2001	06:24	LeoI-2	3600	1.26	0.57	
17Jan2001	07:24		4500	1.32	0.61	
18Jan2001	05:48		4500	1.29	... [2]	

Table 2. The Stellar Sample

Galaxy	star id	V	$(B–V)_o$	$(V–I)_o$	RV_{helio} (km/s)	ref
Sculptor	H400	18.30	0.89	1.04	109	1,2,11,12
	H459	18.14	1.03	1.16	116	
	H461	17.56	1.17	1.35	104	
	H479	17.23	1.20	1.31	98	
	H482	17.65	1.21	1.41	107	
Fornax	M12	18.43	1.33	1.50	54	3,11,12
	M25	18.59	1.49	1.53	49	
	M21	18.37	1.59	1.66	53	
Carina	M2	17.68	1.325	···	221	4,11,12
	M3	17.75	1.415	1.32	227	
	M4	17.81	1.285	1.28	221	
	M10	18.09	1.255	···	210	
	M12	18.08	1.185	1.19	217	
Leo I	M2	19.37	···	1.34	292	5,11,12
	M5	19.37	···	1.44	304	
MW-M55	76	12.55	0.85	···	175	6,7,8
	283	12.75	1.01	···	172	6,7,8
MW-M30	D	12.81	1.00	···	−186	6,9
MW-M68	53	12.76	1.22	···	−96	10

Note. — 1. Hodge 1965; 2. Queloz, Dubath, & Pasquini 1995; 3. Mateo et al. 1991; 4. Mateo et al. 1993; 5. Mateo et al. 1998; 6. Harris 1996, 7. Harris 1975, 8. Alcaino 1975, 9. Alcaino & Liller 1980; 10. Alcaino 1977; 11. Tolstoy et al. in prep; 12. E(V-I) from Dean, Warren & Cousins 1978

Table 3. Equivalent Widths and Atomic Data

Elem	λ Å	χ eV	log gf	M30 D	M55 283	M55 76	M68 53	SCL H400	SCL H459	SCL H461	SCL H479	SCL H482
Fe I	4966.10	3.33	-0.890	66	88	84	74	...	...	...	...	...
	5006.12	2.83	-0.628	108	124	123	116	106	131	129	...	153
	5079.75	0.99	-3.240	116	125	...	136	...	...	...	...	174
	5083.35	0.96	-2.862	125	125	128	137	127	138	155	154	179
	5150.85	0.99	-3.030	115	127	121	129	103	134	145	158	169
	5151.92	1.01	-3.326	108	110	111	118	92	121	137	124	171
	5159.05	4.28	-0.810	14	25	19	17	...	29	32	42	52
	5162.29	4.18	0.020	55	84	71	68	72	83	96	80	100
	5165.41	4.22	-0.040	...	...	...	...	...	75	...	...	...
	5166.28	0.00	-4.200	140	132	137	160	122	160	...	...	181
	5171.61	1.48	-1.751	148	145	149	159	126	164	170	175	198
	5192.34	3.00	-0.520	107	123	117	119	108	140	155	136	147
	5196.08	4.26	-0.450	...	...	23	20	...	...	50	...	...
	5215.19	3.27	-0.930	59	84	78	75	73	102	109	...	122
	5216.28	1.61	-2.102	125	132	130	139	109	152	154	151	185
	5217.30	3.21	-1.270	57	79	70	63	...	92	100	...	121
	5232.95	2.94	-0.067	130	147	143	139	117	150	161	157	193
	5250.21	0.12	-4.700	90	94	94	107	64	114	122	126	149
	5253.02	2.28	-3.810	...	8	...	...	...	...	...	17	40
	5307.37	1.61	-2.812	78	96	91	91	88	105	109	118	138
	5324.19	3.21	-0.100	108	126	127	117	108	145	147	138	175
	5339.93	3.27	-0.680	77	92	94	86	74	101	127	104	140
	5364.86	4.45	0.220	38	65	59	50	58	82	86	80	98
	5367.48	4.42	0.550	51	75	...	60	66	90	89	81	109
	5369.96	4.37	0.540	58	81	73	67	90	87	112	101	113
	5371.50	0.96	-1.644	196	200	202	208	167	...	...	250	...
	5383.37	4.31	0.500	72	89	85	71	62	100	116	...	121
	5389.48	4.42	-0.400	21	36	34	19	...	54	52	41	71
	5393.17	3.24	-0.920	75	92	...	90	69	108	125	104	...
	5397.14	0.91	-1.992	185	176	188	206	148	199	214	228	267
	5400.51	4.37	-0.150	33	56	47	35	29	73	74	66	94
	5405.79	0.99	-1.852	183	180	182	199	161	...	205	229	...
	5415.19	4.39	0.510	61	87	80	71	70	91	108	106	127
	5424.07	4.32	0.520	70	94	91	83	68	108	...	94	129
	5501.48	0.96	-3.050	130	130	132	154	118	154	167	176	182
	5506.79	0.99	-2.790	140	146	146	158	122	152	165	176	219
	5615.66	3.33	0.050	113	129	124	118	104	131	146	139	174
	5956.70	0.86	-4.570	44	58	45	57	...	77	88	100	119
	6003.03	3.88	-1.110	21	36	31	25	26	57	58	51	86
	6024.05	4.55	-0.110	24	55	...	37	34	56	63	62	96

Table 3—Continued

Elem	λ Å	χ eV	log gf	M30 D	M55 283	M55 76	M68 53	SCL H400	SCL H459	SCL H461	SCL H479	SCL H482
	6027.06	4.07	-1.180	11	23	14	15	···	29	45	43	80
	6056.01	4.73	-0.450	···	21	13	11	···	35	34	23	46
	6078.50	4.79	-0.370	···	22	18	11	···	31	30	35	60
	6079.01	4.65	-0.950	···	···	···	···	···	23	···	17	42
	6082.72	2.22	-3.590	···	24	14	10	···	37	41	44	86
	6120.26	0.91	-5.940	···	···	···	···	···	10	···	15	···
	6136.62	2.45	-1.500	103	120	118	120	108	147	153	151	153
	6137.70	2.59	-1.366	103	112	114	111	87	134	140	138	173
	6151.62	2.18	-3.370	15	37	34	26	···	65	60	79	···
	6157.75	4.07	-1.260	13	30	16	11	···	19	36	26	···
	6165.36	4.14	-1.470	···	25	12	11	···	22	18	16	46
	6173.34	2.22	-2.850	58	55	45	67	49	89	92	90	···
	6187.99	3.94	-1.580	···	14	···	15	···	···	32	25	56
	6191.57	2.43	-1.416	114	124	115	117	122	140	148	148	173
	6213.43	2.22	-2.660	55	82	69	82	47	90	100	113	140
	6219.29	2.20	-2.438	70	89	80	84	53	96	109	116	140
	6229.23	2.84	-2.900	···	15	11	···	···	28	34	37	54
	6230.74	2.56	-1.276	110	122	123	119	113	132	158	···	196
	6240.66	2.22	-3.230	17	30	28	24	···	61	53	47	80
	6252.57	2.40	-1.757	93	114	110	111	99	123	134	136	166
	6290.97	4.73	-0.760	···	14	10	···	···	···	34	···	57
	6297.80	2.22	-2.740	46	64	55	68	49	76	103	85	···
	6301.50	3.65	-0.720	42	70	59	72	60	86	98	94	133
	6302.49	3.69	-1.150	18	70	52	38	35	54	55	49	103
	6311.51	2.83	-3.220	···	10	···	···	···	23	26	32	58
	6355.04	2.84	-2.290	21	49	40	34	···	64	68	75	101
	6380.75	4.19	-1.500	···	13	···	···	···	19	25	21	38
	6392.54	2.28	-3.950	···	···	···	···	···	···	···	24	42
	6393.61	2.43	-1.630	107	···	···	119	···	···	···	···	···
	6419.96	4.73	-0.240	12	28	20	14	···	28	31	32	56
	6421.36	2.28	-2.014	94	110	111	125	107	122	135	139	175
	6430.86	2.18	-1.946	103	115	110	114	115	128	141	151	172
	6498.94	0.96	-4.690	35	48	39	72	···	70	85	94	122
	6518.37	2.83	-2.460	13	28	23	30	···	44	50	55	84
	6574.23	0.99	-5.020	20	30	24	···	···	49	56	67	88
	6581.22	1.48	-4.680	···	18	14	···	···	···	···	37	64
	6593.88	2.43	-2.390	50	70	65	···	47	104	105	106	115
	6608.03	2.28	-3.940	···	···	···	···	···	12	24	29	36
	6609.12	2.56	-2.660	26	···	30	···	···	68	77	80	111
Fe II	4923.92	2.89	-1.320	133	136	···	129	142	124	143	143	···

Table 3—Continued

Elem	λ Å	χ eV	log gf	M30 D	M55 283	M55 76	M68 53	SCL H400	SCL H459	SCL H461	SCL H479	SCL H482
	5018.43	2.89	-1.220	145	162	···	143	···	···	···	···	···
	5196.08	4.26	-0.450	···	···	···	···	···	···	···	···	98
	5197.57	3.23	-2.100	64	74	76	62	86	79	91	82	92
	5234.63	3.22	-2.118	66	81	83	65	64	87	90	74	···
	5264.81	3.23	-3.210	20	30	32	21	34	46	44	24	43
	5276.00	3.20	-1.950	79	95	···	81	···	98	···	···	···
	5284.10	2.89	-3.190	37	41	52	42	45	61	61	57	66
	5325.56	3.22	-2.600	···	···	···	···	···	···	···	50	···
	5425.25	3.20	-3.360	15	24	25	19	···	38	36	26	42
	5534.85	3.24	-2.920	33	50	51	48	42	54	···	58	···
	5991.38	3.15	-3.740	13	18	16	15	···	26	21	28	30
	6149.25	3.89	-2.720	11	19	16	13	···	···	···	16	31
	6238.38	3.89	-2.480	11	23	20	16	···	30	33	20	32
	6247.56	3.89	-2.360	25	32	34	22	28	32	40	37	40
	6369.46	2.89	-4.250	···	···	10	···	···	···	···	···	18
	6416.93	3.89	-2.790	9	21	16	···	···	22	18	18	39
	6432.68	2.89	-3.710	18	···	22	18	32	45	30	29	52.0
	6456.39	3.90	-2.080	24	48	42	35	54	44	46	53	68
	6516.08	2.89	-3.450	31	···	44	31	49	47	42	61	65
O I	6300.31	0.00	-9.750	16	7	27	19	···	24	37	46	25
	6363.79	0.02	-10.250	···	···	10	7	···	···	···	18	18
Na I	5682.65	2.10	-0.700	16	···	15	19	···	23	15	12	36
	5688.21	2.10	-0.370	24	56	17	25	···	25	26	16	46
	5889.97	0.00	0.122	···	290	252	···	212	···	···	···	···
	6154.23	2.10	-1.560	···	···	···	···	···	···	···	···	···
	6160.75	2.10	-1.260	···	10	···	···	···	···	···	···	···
Mg I	5172.70	2.71	-0.390	···	···	···	···	256	···	···	···	···
	5528.41	4.35	-0.357	120	128	143	127	124	157	151	151	148
	5711.09	4.35	-1.728	30	35	47	34	37	58	60	50	81
Al I	6696.03	3.14	-1.570	12	37	<5	···	···	<10	<10	<10	<15
	6698.67	3.14	-1.890	8	20	···	···	···	···	···	···	···
Si I	5645.66	4.91	-2.140	···	···	10	···	···	···	···	···	···
	5665.60	4.90	-2.040	···	12	···	···	···	···	···	···	···
	5684.52	4.93	-1.650	12	19	17	16	···	24	25	13	23
	6243.82	5.61	-1.270	···	21	···	···	···	···	···	···	···
	6244.48	5.61	-1.270	···	14	···	12	···	···	···	7	18
Ca I	6102.73	1.88	-0.790	82	102	100	91	85	121	135	121	155
	6122.23	1.89	-0.320	118	132	135	122	129	132	147	139	159
	6161.30	2.52	-1.270	11	24	19	13	···	43	37	30	56
	6166.44	2.52	-1.140	21	30	30	18	17	36	37	27	72

Table 3—Continued

Elem	λ Å	χ eV	log gf	M30 D	M55 283	M55 76	M68 53	SCL H400	SCL H459	SCL H461	SCL H479	SCL H482
	6169.04	2.52	-0.800	24	56	39	42	43	56	73	55	86
	6169.56	2.52	-0.480	45	66	51	47	40	73	78	72	106
	6439.08	2.52	0.390	105	119	126	115	103	140	149	135	148
	6455.60	2.52	-1.290	10	30	19	16	···	27	31	40	39
	6499.65	2.52	-0.820	38	57	49	27	47	60	66	65	94
Sc II	6309.90	1.50	-1.520	11	14	···	19	···	26	18	26	21
Ti I	4840.87	0.90	-0.450	41	60	48	50	···	72	100	···	102
	4913.62	1.87	0.216	17	31	24	18	···	···	39	37	61
	4997.10	0.00	-2.060	28	39	29	38	23	45	54	70	85
	5016.16	0.85	-0.510	44	···	50	50	···	68	75	···	116
	5064.65	0.05	-0.930	89	99	96	101	60	105	119	115	132
	5113.44	1.44	-0.727	···	···	14	11	···	32	24	···	54
	5145.47	1.46	-0.518	···	23	15	···	···	23	37	34	51
	5210.39	0.05	-0.580	95	104	103	115	81	119	137	135	150
	5978.54	1.87	-0.440	···	22	13	···	···	16	20	19	34
Ti II	4798.53	1.08	-2.670	76	73	88	64	···	···	···	···	···
	5129.16	1.89	-1.390	84	···	···	86	60	···	···	···	···
	5154.07	1.57	-1.520	81	···	91	83	80	85	89	89	98
	5226.55	1.57	-1.000	109	120	123	112	106	112	120	114	135
	5381.01	1.57	-1.780	71	77	84	77	76	81	79	···	102
	5418.77	1.58	-2.110	57	66	69	59	61	75	77	76	79
Cr I	5206.04	0.94	0.019	133	···	149	143	123	159	175	180	208
	5409.80	1.03	-0.720	91	111	109	104	97	122	130	139	168
Mn I	5407.42*	2.14	-1.743	···	20	···	···	···	···	···	33	···
	5420.36*	2.14	-1.460	···	···	10	···	···	36	36	35	98
	5432.55*	0.00	-3.795	12	21	14	18	···	57	50	60	130
	5516.77	2.18	-1.847	···	···	···	···	···	···	···	···	43
	6013.51*	3.07	-0.252	···	18	···	10	···	31	27	27	64
	6021.82*	3.08	0.035	14	28	18	21	···	47	50	47	82
Co I	5483.34	1.71	-1.488	22	···	37	33	···	52	62	52	75
	5647.23	2.28	-1.560	···	···	···	···	···	···	···	15	···
Ni I	5476.92	1.83	-0.890	121	···	131	133	112	136	149	141	161
	6176.82	4.09	-0.430	···	16	9	···	···	34	31	15	32
	6177.25	1.83	-3.500	···	···	···	···	···	21	21	10	21
Cu I	5105.50*	1.39	-1.505	21	31	27	26	<15	53	55	57	68
	5700.24	1.64	-2.330	···	···	···	···	···	12	10	···	···
Zn I	4810.54	4.08	-0.170	38	54	55	30	···	64	45	35	74
Y II	4883.69	1.08	0.070	57	70	73	48	···	89	77	48	···
	4900.11	1.03	-0.090	49	···	67	45	···	···	···	52	62
	5087.43	1.08	-0.170	39	55	56	33	86	64	55	38	60

Table 3—Continued

Elem	λ Å	χ eV	log gf	M30 D	M55 283	M55 76	M68 53	SCL H400	SCL H459	SCL H461	SCL H479	SCL H482
	5200.42	0.99	-0.570	28	$\cdots$	44	22	53	66	49	30	56
Ba II	5853.69*	0.60	-1.010	61	99	104	80	127	105	102	83	126
	6141.73*	0.70	-0.077	123	145	158	135	178	167	160	140	172
	6496.91	0.60	-0.380	128	143	156	132	142	146	143	136	156
Nd II	5249.59	0.98	0.217	15	35	32	20	64	45	34	18	30
	5319.82	0.55	-0.194	20	$\cdots$	37	29	52	60	51	28	57
La II	5301.97	0.40	-1.140	3	14	$\cdots$	18	38	15	16	15	40
	5303.52*	0.32	-1.350	5	9	10	14	23	10	10	10	33
	6390.46*	0.32	-1.400	10	12	17	6	17	10	10	8	13
Eu II	6645.13	1.37	0.200	9	18	20	9	37	29	18	17	22

*Hyperfine structure references: Cu I Biehl 1976; Mn I Booth et al. 1983; La II Lawler, Bonvallet, & Sneden 2001; Ba II McWilliam 1998; Eu II Lawler et al. 2001.

Table 4. Equivalent Widths and Atomic Data

Elem	λ Å	χ eV	log gf	Car 10	Car 12	Car 2	Car 3	Car 4	Fnx M12	Fnx M21	Fnx M25	Leo 2	Leo 5
Fe I	4966.10	3.33	-0.890	93	136	···	···	130	130	···	···	···	···
	5006.12	2.83	-0.628	137	169	162	172	···	···	···	202	193	180
	5079.75	0.99	-3.240	···	···	173	···	···	···	···	···	···	···
	5083.35	0.96	-2.862	152	186	193	198	195	···	···	241	210	···
	5150.85	0.99	-3.030	144	186	186	181	200	···	···	211	199	198
	5151.92	1.01	-3.326	139	176	180	188	170	···	···	···	···	···
	5159.05	4.28	-0.810	26	57	56	37	57	39	···	69	67	62
	5162.29	4.18	0.020	78	118	112	106	112	95	···	120	···	134
	5165.41	4.22	-0.040	···	98	86	68	···	···	···	···	···	···
	5166.28	0.00	-4.200	167	201	216	217	217	···	···	···	···	206
	5171.61	1.48	-1.751	177	219	213	220	222	···	···	···	···	227
	5192.34	3.00	-0.520	···	181	180	187	194	···	···	···	···	200
	5196.08	4.26	-0.450	26	68	56	55	···	···	···	···	88	···
	5215.19	3.27	-0.930	91	138	124	···	135	120	···	152	···	140
	5216.28	1.61	-2.102	149	185	192	188	203	···	···	245	226	196
	5217.30	3.21	-1.270	78	129	126	122	132	100	···	139	136	121
	5232.95	2.94	-0.067	157	204	196	190	201	···	···	251	···	···
	5250.21	0.12	-4.700	116	168	175	182	186	···	···	224	···	196
	5253.02	2.28	-3.810	18	39	37	26	40	34	100	73	68	39
	5307.37	1.61	-2.812	107	146	141	151	144	148	···	172	176	156
	5324.19	3.21	-0.100	140	196	181	189	186	···	···	228	···	194
	5339.93	3.27	-0.680	119	127	152	150	146	129	···	158	157	131
	5364.86	4.45	0.220	63	97	···	89	102	90	···	132	136	100
	5367.48	4.42	0.550	73	116	104	103	···	117	···	···	···	120
	5369.96	4.37	0.540	86	128	122	108	117	···	···	133	···	131
	5371.50	0.96	-1.644	233	···	···	315	···	···	···	···	···	···
	5383.37	4.31	0.500	93	122	131	130	131	···	···	139	157	139
	5389.48	4.42	-0.400	···	82	78	76	71	75	···	102	105	76
	5393.17	3.24	-0.920	110	149	142	···	153	124	···	174	···	···
	5397.14	0.91	-1.992	···	···	···	281	···	···	···	···	···	···
	5400.51	4.37	-0.150	59	···	92	74	94	95	···	···	···	114
	5405.79	0.99	-1.852	209	···	···	265	···	···	···	···	···	···
	5415.19	4.39	0.510	90	119	122	···	118	125	···	131	150	115
	5424.07	4.32	0.520	103	144	134	126	137	129	···	140	180	167
	5501.48	0.96	-3.050	167	197	205	208	212	···	···	260	···	217
	5506.79	0.99	-2.790	168	212	216	210	224	···	···	···	···	254
	5615.66	3.33	0.050	129	195	178	175	177	···	···	204	211	203
	5731.76	4.25	-1.300	···	···	···	···	···	···	99	···	···	···
	5732.30	4.99	-1.560	···	···	···	···	···	···	30	···	···	···
	5738.23	4.22	-2.340	···	···	···	···	···	···	26	···	···	···

Table 4—Continued

Elem	λ Å	χ eV	log gf	Car 10	Car 12	Car 2	Car 3	Car 4	Fnx M12	Fnx M21	Fnx M25	Leo 2	Leo 5
	5853.15	1.48	-5.280	···	···	···	···	···	···	78	···	···	···
	5855.08	4.60	-1.760	···	···	···	···	···	···	51	···	···	···
	5861.11	4.28	-2.450	···	···	···	···	···	···	26	···	···	···
	5905.67	4.65	-0.730	···	···	···	···	···	···	80	···	···	···
	5929.68	4.54	-1.410	···	···	···	···	···	···	71	···	···	···
	5930.18	4.65	-0.230	···	···	···	···	···	···	94	···	···	···
	5933.80	4.63	-2.230	···	···	···	···	···	···	38	···	···	···
	5952.72	3.98	-1.440	···	···	···	···	···	···	70	···	···	···
	5956.70	0.86	-4.570	85	139	137	140	140	146	···	173	176	135
	6003.03	3.88	-1.110	37	74	82	80	77	90	110	102	108	72
	6015.24	2.22	-4.680	···	···	···	···	···	···	63	···	···	···
	6019.36	3.57	-3.360	···	···	···	···	···	···	43	···	···	···
	6024.05	4.55	-0.110	46	92	88	86	85	97	128	115	111	90
	6027.06	4.07	-1.180	22	66	52	60	60	67	126	98	86	61
	6056.01	4.73	-0.450	23	51	43	35	44	40	82	77	62	63
	6078.50	4.79	-0.370	11	61	37	37	51	52	76	81	81	46
	6079.01	4.65	-0.950	···	29	···	15	26	25	53	42	59	29
	6082.72	2.22	-3.590	···	77	65	49	63	74	···	123	98	53
	6105.13	4.54	-2.050	···	···	···	···	···	···	21	···	···	···
	6120.26	0.91	-5.940	···	37	36	···	40	47	128	78	66	31
	6136.62	2.45	-1.500	147	176	177	187	180	···	···	223	204	210
	6137.70	2.59	-1.366	134	176	178	182	180	···	···	233	···	189
	6151.62	2.18	-3.370	36	96	97	90	92	97	···	140	119	111
	6157.75	4.07	-1.260	32	69	56	39	56	52	···	105	99	63
	6165.36	4.14	-1.470	···	39	37	27	42	23	80	58	75	38
	6173.34	2.22	-2.850	66	117	115	105	113	131	···	158	156	112
	6187.99	3.94	-1.580	···	47	28	28	33	40	95	72	83	53
	6191.57	2.43	-1.416	129	170	175	173	174	···	···	240	202	195
	6213.43	2.22	-2.660	90	135	135	130	139	140	···	161	168	148
	6219.29	2.20	-2.438	102	140	145	130	148	···	···	190	170	134
	6220.78	3.88	-2.460	···	···	···	···	···	···	29	···	···	···
	6229.23	2.84	-2.900	19	63	52	44	56	65	122	107	85	52
	6230.74	2.56	-1.276	141	195	202	186	207	···	···	···	···	210
	6232.64	3.65	-0.960	···	···	···	···	···	···	138	···	···	···
	6240.66	2.22	-3.230	30	90	91	72	81	92	132	135	122	87
	6252.57	2.40	-1.757	123	167	165	176	176	···	···	221	201	181
	6270.23	2.85	-2.610	···	···	···	···	···	···	133	···	···	···
	6290.97	4.73	-0.760	14	44	36	37	30	30	79	66	68	40
	6297.80	2.22	-2.740	81	125	124	137	140	149	···	175	165	127
	6301.50	3.65	-0.720	92	113	120	141	122	121	···	154	144	122

Table 4—Continued

Elem	λ Å	χ eV	log gf	Car 10	Car 12	Car 2	Car 3	Car 4	Fnx M12	Fnx M21	Fnx M25	Leo 2	Leo 5
	6302.49	3.69	-1.150	36	86	80	69	81	97	132	125	100	99
	6311.51	2.83	-3.220	10	38	34	23	44	50	85	84	83	51
	6353.84	0.91	-6.430	···	11	12	16	12	···	65	44	45	···
	6355.04	2.84	-2.290	55	100	106	89	104	109	···	154	···	119
	6380.75	4.19	-1.500	···	50	44	38	···	44	94	77	71	52
	6392.54	2.28	-3.950	10	47	46	23	44	32	92	69	94	40
	6393.61	2.43	-1.630	129	170	179	182	178	···	···	···	···	···
	6419.96	4.73	-0.240	31	63	64	52	59	52	110	92	75	66
	6421.36	2.28	-2.014	123	163	160	174	173	···	···	205	192	170
	6430.86	2.18	-1.946	133	172	169	191	180	···	···	240	206	195
	6481.87	2.27	-2.980	···	···	···	···	···	···	150	···	···	···
	6498.94	0.96	-4.690	66	122	128	108	130	139	···	175	165	133
	6518.37	2.83	-2.460	36	92	81	73	86	81	130	126	102	97
	6533.93	4.55	-1.460	···	···	···	···	···	···	74	···	···	···
	6574.23	0.99	-5.020	41	93	98	89	99	115	···	160	141	128
	6581.22	1.48	-4.680	···	66	54	61	66	77	···	116	99	69
	6593.88	2.43	-2.390	89	129	132	135	140	145	···	172	161	130
	6597.56	4.79	-1.070	···	···	···	···	···	···	58	···	···	···
	6608.03	2.28	-3.940	···	45	35	30	42	33	123	95	70	48
	6609.12	2.56	-2.660	56	111	107	102	108	111	···	158	140	132
	6627.54	4.54	-1.680	···	···	···	···	···	···	59	···	···	···
	6646.93	2.60	-3.990	···	···	···	···	···	···	80	···	···	···
	6653.85	4.15	-2.520	···	···	···	···	···	···	28	···	···	···
	6699.14	4.59	-2.190	···	···	···	···	···	···	16	···	···	···
	6704.48	4.21	-2.660	···	···	···	···	···	···	22	···	···	···
	6726.67	4.60	-1.000	···	···	···	···	···	···	59	···	···	···
	6733.15	4.63	-1.580	···	···	···	···	···	···	33	···	···	···
	6786.86	4.19	-2.070	···	···	···	···	···	···	49	···	···	···
Fe II	4923.92	2.89	-1.320	138	161	156	···	157	···	···	170	···	154
	5197.57	3.23	-2.100	89	109	91	···	93	81	···	118	···	98
	5234.63	3.22	-2.118	86	92	···	···	···	105	···	104	···	···
	5264.81	3.23	-3.210	38	48	49	51	40	50	51	52	52	34
	5276.00	3.20	-1.950	97	···	···	···	···	108	···	···	···	···
	5284.10	2.89	-3.190	48	76	75	84	82	71	···	66	81	61
	5325.56	3.22	-2.600	···	65	···	···	49	···	···	···	···	···
	5425.25	3.20	-3.360	25	43	40	51	34	39	38	44	45	52
	5534.85	3.24	-2.920	50	72	···	···	69	75	···	62	···	63
	5991.38	3.15	-3.740	21	34	27	34	37	33	···	30	44	28
	6149.25	3.89	-2.720	26	···	25	28	26	24	···	37	···	19
	6238.38	3.89	-2.480	34	40	30	44	33	38	···	58	47	48

Table 4—Continued

Elem	λ Å	χ eV	log gf	Car 10	Car 12	Car 2	Car 3	Car 4	Fnx M12	Fnx M21	Fnx M25	Leo 2	Leo 5
	6247.56	3.89	-2.360	45	43	49	53	49	51	47	54	59	38
	6369.46	2.89	-4.250	···	30	18	32	25	20	···	21	30	16
	6416.93	3.89	-2.790	···	30	28	25	30	33	50	···	37	29
	6432.68	2.89	-3.710	33	52	40	43	42	59	54	56	51	31
	6456.39	3.90	-2.080	47	77	44	63	48	54	40	55	71	80
	6516.08	2.89	-3.450	50	64	57	66	52	64	···	78	73	···
O I	6300.31	0.00	-9.750	17	39	44	30	40	24	76	76	50	68
	6363.79	0.02	-10.25	9	16	27	15	17	18	36	27	20	24
Na I	5682.65	2.10	-0.700	···	35	26	···	27	19	140	64	78	30
	5688.21	2.10	-0.370	···	47	41	···	52	33	134	77	79	46
	5889.97	0.00	0.122	215	···	···	272	···	295	···	457	···	···
	6154.23	2.10	-1.560	···	14	···	···	···	···	93	27	···	···
	6160.75	2.10	-1.260	···	19	···	···	9	···	94	36	28	···
Mg I	5172.70	2.71	-0.390	···	···	···	···	···	415	1699	665	···	···
	5183.27	2.70	-0.170	···	···	···	···	···	460	1981	···	···	···
	5528.41	4.35	-0.357	109	181	165	126	179	159	255	180	171	167
	5711.09	4.35	-1.728	37	85	84	36	77	70	138	111	93	90
Al I	6696.03	3.14	-1.570	···	13	<14	<12	14	···	65	33	17	25
	6698.67	3.14	-1.890	···	···	···	···	···	···	37	···	···	···
Si I	5645.66	4.91	-2.140	···	···	12	···	17	···	49	···	···	···
	5665.60	4.90	-2.040	···	32	19	···	13	19	···	···	23	···
	5684.52	4.93	-1.650	···	29	26	11	36	26	55	···	···	···
	6145.02	5.61	-1.370	···	18	···	···	19	···	26	···	···	···
	6243.82	5.61	-1.270	···	17	···	···	14	···	35	···	···	···
	6244.48	5.61	-1.270	9	20	12	···	12	23	33	···	27	···
Ca I	6102.73	1.88	-0.790	86	144	147	125	142	145	232	202	178	152
	6122.23	1.89	-0.320	123	162	184	154	185	160	247	234	193	195
	6161.30	2.52	-1.270	···	68	52	···	60	56	142	103	95	71
	6166.44	2.52	-1.140	18	67	68	40	61	66	158	113	93	59
	6169.04	2.52	-0.800	33	93	99	59	86	106	169	148	116	94
	6169.56	2.52	-0.480	41	108	103	77	99	111	169	147	125	···
	6439.08	2.52	0.390	116	154	152	138	166	189	260	216	183	171
	6455.60	2.52	-1.290	10	51	45	···	55	57	145	···	90	67
	6499.65	2.52	-0.820	39	104	93	46	90	103	176	122	115	93
Sc II	6309.90	1.50	-1.520	30	45	28	13	26	42	74	51	18	···
Ti I	4840.87	0.90	-0.450	50	124	109	80	124	131	···	···	145	147
	4913.62	1.87	0.216	24	82	61	29	67	60	145	105	100	80
	4997.10	0.00	-2.060	28	113	113	66	107	119	232	153	148	113
	5014.24	0.81	0.910	···	···	···	···	···	225	···	···	204	···
	5016.16	0.85	-0.510	54	120	115	74	126	97	215	150	130	119

Table 4—Continued

Elem	λ Å	χ eV	log gf	Car 10	Car 12	Car 2	Car 3	Car 4	Fnx M12	Fnx M21	Fnx M25	Leo 2	Leo 5
	5064.65	0.05	-0.930	103	165	···	···	177	183	334	205	···	191
	5113.44	1.44	-0.727	19	55	49	16	49	55	155	80	64	58
	5145.47	1.46	-0.518	12	58	64	···	63	57	163	98	···	61
	5210.39	0.05	-0.580	131	169	181	152	182	171	330	252	···	195
	5978.54	1.87	-0.440	···	37	35	···	33	37	154	101	54	44
	6303.77	1.44	-1.570	···	18	25	···	18	30	137	58	48	41
Ti II	4798.53	1.08	-2.670	53	77	75	69	69	···	···	···	102	82
	5129.16	1.89	-1.390	72	115	106	···	···	107	107	···	130	144
	5154.07	1.57	-1.520	91	114	100	103	112	104	184	110	121	121
	5226.55	1.57	-1.000	114	134	140	140	145	135	199	···	···	176
	5381.01	1.57	-1.780	76	111	116	111	112	91	···	107	···	146
	5418.77	1.58	-2.110	57	90	98	85	97	75	113	80	96	109
Cr I	5206.04	0.94	0.019	163	227	243	247	219	228	499	···	···	255
	5409.80	1.03	-0.720	127	185	193	189	190	193	410	277	···	211
Mn I	5407.42*	2.14	-1.743	···	72	56	25	66	74	197	···	···	···
	5420.36*	2.14	-1.460	14	93	69	41	79	79	231	165	···	100
	5432.55*	0.00	-3.795	40	134	122	96	136	122	···	206	185	146
	5483.34	1.71	-1.488	···	···	95	···	···	···	···	···	···	···
	5516.77	2.18	-1.847	···	40	35	18	32	33	160	125	107	53
	5647.23	2.28	-1.560	···	···	26	···	···	···	···	···	···	···
	6013.51*	3.07	-0.252	···	62	55	41	58	60	169	125	116	57
	6021.82*	3.08	0.035	32	90	71	64	83	79	162	140	134	86
Co I	5483.34	1.71	-1.488	27	96	···	···	96	115	152	130	118	···
	5647.23	2.28	-1.560	···	27	···	18	22	23	76	55	41	···
	6454.99	3.63	-0.250	···	···	···	···	19	···	35	···	20	···
Ni I	5476.92	1.83	-0.890	144	176	181	190	183	162	240	225	196	198
	6176.82	4.09	-0.430	···	42	22	29	35	40	90	57	43	41
	6177.25	1.83	-3.500	···	37	29	20	34	30	90	63	44	28
	6223.99	4.10	-0.990	···	···	···	···	15	18	39	···	18	15
Cu I	5105.50*	1.39	-1.505	23	106	98	73	106	101	210	132	151	116
	5700.24	1.64	-2.330	···	28	···	···	24	24	150	70	64	23
Zn I	4810.54	4.08	-0.170	39	59	65	47	57	47	···	75	18	51
Y II	4883.69	1.08	0.070	69	95	83	93	93	72	209	115	106	74
	4900.11	1.03	-0.090	65	79	86	···	86	79	143	···	89	···
	5087.43	1.08	-0.170	72	73	71	80	71	80	132	83	82	55
	5200.42	0.99	-0.570	58	60	···	50	75	···	143	73	65	65
Ba II	5853.69*	0.60	-1.010	118	136	139	140	133	136	225	···	144	126
	6141.73*	0.70	-0.077	180	177	194	211	193	190	355	256	239	202
	6496.91	0.60	-0.380	172	174	175	210	179	191	290	250	207	201
Nd II	5249.59	0.98	0.217	64	64	60	65	62	65	138	87	81	···

Table 4—Continued

Elem	λ Å	χ eV	log gf	Car 10	Car 12	Car 2	Car 3	Car 4	Fnx M12	Fnx M21	Fnx M25	Leo 2	Leo 5
	5319.82	0.55	-0.194	75	65	68	85	79	71	133	98	93	77
La II	5301.97	0.40	-1.140	20	40	27	28	38	22	161	82	115	70
	5303.52*	0.32	-1.350	27	34	27	25	29	17	84	48	61	22
	6390.46*	0.32	-1.400	24	24	23	23	32	23	107	41	43	43
Eu II	6645.13	1.37	0.200	45	19	17	39	24	35	87	52	66	36

*Hyperfine structure references: Cu I Biehl 1976; Mn I Booth et al. 1983; La II Lawler, Bonvallet, & Sneden 2001; Ba II McWilliam 1998; Eu II Lawler et al. 2001.

Table 5. Atmospheric Parameters

OBJ	T_{eff} (K)	log g	ξ ($km\,s^{-1}$)	[FeI/H]
M30-D	4400	0.50	2.0	-2.30
M55-283	4600	1.20	1.65	-1.75
M55-76	4550	0.90	1.9	-1.99
M68-53	4300	0.30	2.0	-2.21
Scl-400	4650	0.90	1.7	-1.98
Scl-459	4500	1.00	1.65	-1.66
Scl-461	4500	1.20	1.7	-1.56
Scl-479	4325	0.70	1.7	-1.77
Scl-482	4400	1.10	1.7	-1.24
Fnx-25	4025	0.00	2.0	-1.21
Fnx-12	4150	0.00	2.1	-1.60
Fnx-21	4000	0.50	1.7	-0.67
Leo-2	4200	0.50	1.85	-1.06
Leo-5	4250	0.80	2.2	-1.52
Car-2	4250	0.55	2.1	-1.60
Car-3	4250	0.20	2.2	-1.65
Car-4	4200	0.40	2.1	-1.59
Car-10	4375	0.40	2.0	-1.94
Car-12	4300	0.60	1.9	-1.41

Table 6. Abundance Uncertainties for Car-2

Elem	$\Delta T_{\rm eff}$ $-100\,K$	Δlog g -0.2	$\Delta\xi$ $-0.2\,{\rm km\,s^{-1}}$	[M/H] -0.15	Cont. 4mÅ	$\Delta T_{\rm eff}$,Δlog g,$\Delta\xi$ $-100,-0.25,-0.1$
[FeI/H]	-0.11	+0.02	+0.11	+0.02	-0.06	-0.05
[FeII/H]	+0.10	-0.07	+0.05	-0.03	-0.08	+0.03
[OI/FeI]	+0.11	-0.11	-0.11	-0.07	-0.01	-0.05
[NaI/FeI]	+0.02	+0.01	-0.10	+0.00	-0.02	+0.00
[MgI/FeI]	+0.03	+0.03	-0.03	+0.01	+0.01	+0.05
[SiI/FeI]	+0.11	-0.02	-0.11	-0.02	-0.09	+0.04
[CaI/FeI]	-0.03	+0.01	-0.03	+0.01	+0.00	-0.01
[ScII/FeI]	+0.13	-0.09	-0.10	-0.06	-0.02	-0.02
[TiI/FeI]	-0.10	+0.01	-0.04	+0.01	-0.01	-0.08
[TiII/FeI]	+0.13	-0.06	+0.01	-0.04	-0.01	+0.08
[CrI/FeI]	-0.10	+0.03	+0.04	+0.01	+0.01	-0.02
[MnI/FeI]	-0.06	+0.01	-0.06	+0.01	+0.00	-0.07
[NiI/FeI]	+0.02	-0.01	-0.04	+0.02	-0.02	-0.01
[CuI/FeI]	+0.05	+0.00	-0.05	+0.02	-0.01	-0.04
[ZnI/FeI]	+0.18	-0.02	-0.04	-0.02	-0.02	+0.17
[YII/FeI]	+0.12	-0.05	-0.01	-0.04	+0.03	+0.06
[BaII/FeI]	+0.09	-0.09	+0.08	-0.06	+0.00	+0.04
[NdII/FeI]	+0.10	-0.07	-0.05	-0.04	+0.00	+0.00
[LaII/FeI]	+0.10	-0.09	-0.10	-0.04	-0.04	-0.05
[EuII/FeI]	+0.12	-0.10	-0.10	-0.06	-0.07	-0.03

Note. — The last column is the abundance uncertainty when $T_{\rm eff}$ is changed by -100K *and* the corresponding changes that would occur in log g and microturbulence are taken into account holistically.

Table 7. Adopted Internal Abundance Uncertainties

Elem	σdSph	σSTND
[OI/FeI]	0.10	0.10
[NaI/FeI]	0.05	0.05
[MgI/FeI]	0.05	0.05
[AlI/FeI]	0.07	0.06
[SiI/FeI]	0.08	0.05
[CaI/FeI]	0.02	0.02
[ScII/FeI]	0.07	0.07
[TiI/FeI]	0.07	0.07
[TiII/FeI]	0.08	0.08
[CrI/FeI]	0.05	0.05
[MnI/FeI]	0.07	0.07
[FeI/H]	0.07	0.06
[FeII/H]	0.11	0.08
[CoI/FeI]	0.06	0.06
[NiI/FeI]	0.05	0.05
[CuI/FeI]	0.09	0.09
[ZnI/FeI]	0.13	0.13
[YII/FeI]	0.06	0.06
[BaII/FeI]	0.08	0.08
[NdII/FeI]	0.06	0.06
[LaII/FeI]	0.14	0.16
[EuII/FeI]	0.09	0.08
[YII/H]	0.15	0.10
[BaII/YII]	0.04	0.04
[EuII/H]	0.05	0.05
[BaII/EuII]	0.10	0.09
[LaII/EuII]	0.04	0.04
[NdII/EuII]	0.08	0.07

Note. — The average internal errors are derived from a combination of the continuum uncertainties, metallicity uncertainties, and the stellar parameter uncertainties. The globular cluster standard stars often have smaller internal errors since the uncertainties in the continuum placement are significantly smaller.

Table 8. Globular Cluster Star Abundances

Elem	SUN*		M30-D AVG (Δ_r)	M68-53 AVG (Δ_r)	M55-76 AVG (Δ_r)	M55-283 AVG (Δ_r)
Fe	7.52	[FeI/H]	−2.30 (0.01) 62	−2.21 (0.02) 69	−1.99 (0.01) 65	−1.75 (0.02) 71
—	—	[FeII/H]	−2.32 (0.04)S	−2.24 (0.04)S	−1.98 (0.03)I	−1.77 (0.04)S
O	8.83	[OI/FeI]	+0.26 (0.11)I	+0.19 (0.10)I	+0.48 (0.08)I	−0.22 (0.13)I
Na	6.33	[NaI/FeI]	+0.27 (0.08)I	+0.21 (0.10)S	−0.10 (0.09)S	+0.12 (0.08)I
Mg	7.58	[MgI/FeI]	+0.52 (0.09)S	+0.50 (0.11)S	+0.54 (0.10)S	+0.11 (0.11)S
Al	6.47	[AlI/FeI]	+1.13 (0.08)E	···	< +0.38	+1.15 (0.09)I
Si	7.55	[SiI/FeI]	+0.50 (0.11)I	+0.66 (0.13)S	+0.49 (0.11)S	+0.42 (0.10)S
Ca	6.36	[CaI/FeI]	+0.36 (0.04)S	+0.29 (0.05)I	+0.38 (0.05)S	+0.30 (0.04)I
Sc	3.10	[ScII/FeI]	−0.14 (0.11)I	−0.02 (0.14)I	···	−0.20 (0.13)I
Ti	4.99	[TiI/FeI]	+0.15 (0.05)S	+0.08 (0.05)I	+0.11 (0.04)I	+0.10 (0.06)S
—	—	[TiII/FeI]	+0.23 (0.09)S	+0.14 (0.07)S	+0.26 (0.10)S	+0.17 (0.07)S
Cr	5.67	[CrI/FeI]	−0.25 (0.08)I	−0.32 (0.10)I	−0.09 (0.08)I	−0.08 (0.13)I
Mn	5.39	[MnI/FeI]	−0.45(0.10)S	−0.48 (0.10)I	−0.48 (0.06)I	−0.38 (0.13)S
Co	4.92	[CoI/FeI]	+0.18 (0.11)I	+0.18 (0.14)I	+0.30 (0.11)I	···
Ni	6.25	[NiI/FeI]	+0.01 (0.11)I	−0.04 (0.14)I	−0.01 (0.08)I	−0.01 (0.13)I
Cu	4.21	[CuI/FeI]	−0.68 (0.11)I	−0.78 (0.14)I	−0.74 (0.11)I	−0.87 (0.13)I
Zn	4.60	[ZnI/FeI]	+0.14 (0.11)I	−0.09 (0.14)I	+0.17 (0.11)I	+0.03 (0.13)I
Y	2.24	[YII/FeI]	−0.39 (0.06)I	−0.65 (0.07)I	−0.22 (0.06)I	−0.28 (0.09)I
Ba	2.13	[BaII/FeI]	−0.29 (0.11)S	−0.29 (0.08)I	+0.32 (0.06)I	+0.32 (0.08)I
Nd	1.50	[NdII/FeI]	−0.11 (0.08)I	−0.10 (0.10)I	+0.18 (0.08)I	+0.22 (0.13)I
La	1.22	[LaII/FeI]	−0.14 (0.17)E	+0.04 (0.17)S	+0.24 (0.11)I	+0.08 (0.08)I
Eu	0.51	[EuII/FeI]	+0.24 (0.11)I	+0.12 (0.14)I	+0.59 (0.11)I	+0.48 (0.13)I

*Solar abundances are from Grevesse & Sauval (1998).

The errors quoted here represent only the random errors. These are computed by one of three methods (see text):
I = This random error assumes that the random error of the lines of this species behave in a way similiar to those of Fe I. $\sigma_{Fe}/\sqrt{N}$
S = This random error is based on the standard deviation of the abundance of this species. $\sigma_{el}/\sqrt{N}$
E = This random error is based upon an error computed from the suggested EW error for the these lines. See Cayrel (1988).
For iron, the number of lines used to compute the standard deviation of the mean is given.

Table 9. Carina Abundances

Elem	SUN		Car-4 AVG (Δ_r)	Car-3 AVG (Δ_r)	Car-2 AVG (Δ_r)	Car-12 AVG (Δ_r)	Car-10 AVG (Δ_r)
Fe	7.52	[FeI/H]	−1.59 (0.02) 71	−1.65 (0.02) 74	−1.60 (0.02) 74	−1.41 (0.02) 75	−1.94 (0.02) 66
—	—	[FeII/H]	−1.60 (0.05)S	−1.63 (0.04)I	−1.61 (0.04)I	−1.38 (0.04)S	−1.94 (0.04))I
O	8.83	[OI/FeI]	+0.22 (0.09)I	+0.04 (0.12)I	+0.44 (0.12)S	+0.17 (0.10)I	+0.08 (0.19)I
Na	6.33	[NaI/FeI]	−0.35 (0.08)I	−0.58 (0.17)I	−0.38 (0.10)I	−0.26 (0.11)S	−0.66 (0.15)I
Mg	7.58	[MgI/FeI]	+0.26 (0.09)S	−0.27 (0.12)I	+0.23 (0.10)I	+0.24 (0.10)I	+0.06 (0.11)I
Al	6.47	[AlI/FeI]	+0.20 (0.13)I	< +0.27	< +0.24	+0.03 (0.16)E	···
Si	7.55	[SiI/FeI]	+0.25 (0.06)S	−0.28 (0.17)I	+0.18 (0.07)I	+0.22 (0.07)S	+0.38 (0.22)I
Ca	6.36	[CaI/FeI]	+0.14 (0.04)I	−0.10 (0.06)I	+0.20 (0.05)I	+0.12 (0.05)I	−0.02 (0.05)I
Sc	3.10	[ScII/FeI]	−0.29 (0.13)I	−0.71 (0.17)I	−0.19 (0.14)I	+0.03 (0.14)I	+0.05 (0.15)I
Ti	4.99	[TiI/FeI]	+0.03 (0.04)I	−0.41 (0.07)I	+0.07 (0.05)I	+0.04 (0.05)S	+0.11 (0.05)I
—	—	[TiII/FeI]	+0.01 (0.08)S	−0.13 (0.08)I	+0.05 (0.08)S	+0.04 (0.07)S	+0.16 (0.06))I
Cr	5.67	[CrI/FeI]	−0.11 (0.16)S	+0.20 (0.12)I	+0.12 (0.10)I	−0.01 (0.11)S	−0.19 (0.11)I
Mn	5.39	[MnI/FeI]	−0.32 (0.06)I	−0.44 (0.08)I	−0.33 (0.06)I	−0.32 (0.06)I	−0.42 (0.09)S
Co	4.92	[CoI/FeI]	+0.10 (0.12)S	−0.08 (0.17)I	···	+0.07 (0.14)S	−0.16 (0.15)I
Ni	6.25	[NiI/FeI]	−0.04 (0.07)I	−0.07 (0.10)I	−0.15 (0.08)I	−0.06 (0.08)I	−0.08 (0.15)I
Cu	4.21	[CuI/FeI]	−0.63 (0.12)I	−0.85 (0.12)I	−0.63 (0.08)I	−0.61 (0.14)I	< −0.60
Zn	4.60	[ZnI/FeI]	−0.10 (0.13)I	−0.30 (0.17)I	+0.04 (0.14)I	−0.22 (0.14)I	−0.20 (0.15)I
Y	2.24	[YII/FeI]	−0.38 (0.07)I	−0.49 (0.10)I	−0.45 (0.08)I	−0.46 (0.07)I	−0.31 (0.08)I
Ba	2.13	[BaII/FeI]	+0.02 (0.08)I	+0.20 (0.10)I	+0.11 (0.08)I	+0.11 (0.08)I	+0.25 (0.09)I
Nd	1.50	[NdII/FeI]	+0.23 (0.09)I	+0.26 (0.12)I	+0.17 (0.10)I	+0.14 (0.10)I	+0.57 (0.11)I
La	1.22	[LaII/FeI]	+0.12 (0.08)I	−0.06 (0.10)I	+0.05 (0.08)I	+0.11 (0.09)I	+0.25 (0.09)I
Eu	0.51	[EuII/FeI]	+0.19 (0.13)I	+0.39 (0.17)I	+0.07 (0.14)I	+0.04 (0.14)I	+0.80 (0.15)I

See Table 8 for Table Notes

Table 10. Sculptor Abundances

Elem	SUN		Scl-459 AVG (Δ_r)	Scl-479 AVG (Δ_r)	Scl-461 AVG (Δ_r)	Scl-482 AVG (Δ_r)	Scl-400 AVG (Δ_r)
Fe	7.52	[FeI/H]	−1.66 (0.02) 68	−1.77 (0.02) 67	−1.56 (0.02) 67	−1.24 (0.02) 67	−1.98 (0.03) 45
—	—	[FeII/H]	−1.65 (0.04)I	−1.79 (0.05)S	−1.58 (0.04)I	−1.26 (0.05)I	−1.94 (0.06))I
O	8.83	[OI/FeI]	+0.22 (0.15)I	+0.48 (0.11)I	+0.44 (0.16)I	+0.18 (0.18)S	···
Na	6.33	[NaI/FeI]	−0.33 (0.14)S	−0.59 (0.11)I	−0.55 (0.11)I	−0.55 (0.13)I	−0.16 (0.20)I
Mg	7.58	[MgI/FeI]	+0.36 (0.13)S	+0.26 (0.16)S	+0.18 (0.11)I	+0.09 (0.13)I	+0.37 (0.12)I
Al	6.47	[AlI/FeI]	< +0.30	< +0.30	< +0.19	< −0.02	···
Si	7.55	[SiI/FeI]	+0.22 (0.15)I	+0.00 (0.22)I	+0.14 (0.16)I	−0.07 (0.15)S	···
Ca	6.36	[CaI/FeI]	+0.24 (0.05)I	+0.17 (0.05)I	+0.22 (0.06)S	+0.06 (0.06)I	+0.38 (0.09)S
Sc	3.10	[ScII/FeI]	+0.01 (0.15)I	−0.05 (0.15)I	−0.22 (0.16)I	−0.38 (0.19)I	···
Ti	4.99	[TiI/FeI]	−0.05 (0.05)I	−0.05 (0.06)I	+0.00 (0.06)S	−0.17 (0.06)I	−0.07 (0.13)S
—	—	[TiII/FeI]	−0.01 (0.08)I	+0.02 (0.09)S	−0.01 (0.08)I	−0.01 (0.10)I	+0.00 (0.09))I
Cr	5.67	[CrI/FeI]	−0.21 (0.11)I	−0.07 (0.11)I	−0.18 (0.11)I	−0.14 (0.13)I	−0.13 (0.14)I
Mn	5.39	[MnI/FeI]	−0.34 (0.08)I	−0.39 (0.09)S	−0.49 (0.08)I	−0.40 (0.09)I	···
Co	4.92	[CoI/FeI]	+0.13 (0.15)I	+0.01 (0.11)I	+0.17 (0.16)I	−0.07 (0.19)I	···
Ni	6.25	[NiI/FeI]	+0.11 (0.12)S	−0.24 (0.09)I	+0.04 (0.09)I	−0.28 (0.11)I	+0.01 (0.20)I
Cu	4.21	[CuI/FeI]	−1.05 (0.15)I	−0.83 (0.15)I	−0.79 (0.11)I	−1.13 (0.19)I	< −0.46
Zn	4.60	[ZnI/FeI]	+0.17 (0.15)I	−0.38 (0.15)I	−0.33 (0.15)I	+0.08 (0.19)I	···
Y	2.24	[YII/FeI]	−0.05 (0.12)S	−0.79 (0.08)I	−0.38 (0.09)I	−0.64 (0.11)I	+0.21 (0.23)S
Ba	2.13	[BaII/FeI]	+0.33 (0.09)I	−0.19 (0.09)I	+0.18 (0.09)I	+0.23 (0.11)I	+0.73 (0.17)S
Nd	1.50	[NdII/FeI]	+0.35 (0.11)I	−0.36 (0.11)I	+0.11 (0.11)I	−0.14 (0.19)S	+0.72 (0.20)S
La	1.22	[LaII/FeI]	−0.08 (0.09)I	−0.35 (0.15)E	−0.09 (0.12)E	+0.10 (0.19)I	+0.59 (0.13)S
Eu	0.51	[EuII/FeI]	+0.63 (0.15)I	+0.25 (0.15)I	+0.32 (0.16)I	+0.20 (0.19)I	+1.00 (0.20)I

See Table 8 for Table Notes

Table 11. Fornax and Leo Abundances

Elem	SUN		Fnx-12 AVG (Δ_r)	Fnx-25 AVG (Δ_r)	Fnx-21 AVG (Δ_r)	Leo-5 AVG (Δ_r)	Leo-2 AVG (Δ_r)
Fe	7.52	[FeI/H]	−1.60 (0.02) 48	−1.21 (0.02) 64	−0.67 (0.03) 55	−1.52 (0.02) 67	−1.06 (0.02) 55
—	—	[FeII/H]	−1.59 (0.05)S	−1.17 (0.04)I	−0.73 (0.13)S	−1.48 (0.05)I	−1.10 (0.05))I
O	8.83	[OI/FeI]	−0.02 (0.18)S	+0.17 (0.11)I	+0.12 (0.17)I	+0.53 (0.13)I	−0.04 (0.13)I
Na	6.33	[NaI/FeI]	−0.51 (0.08)I	−0.31 (0.08)I	+0.02 (0.12)I	−0.43 (0.13)I	−0.36 (0.10)I
Mg	7.58	[MgI/FeI]	+0.09 (0.07)I	+0.02 (0.09)I	+0.20 (0.12)I	+0.12 (0.13)I	−0.19 (0.13)I
Al	6.47	[AlI/FeI]	···	+0.09 (0.16)I	−0.04 (0.24)I	+0.42 (0.18)I	−0.28 (0.18)I
Si	7.55	[SiI/FeI]	+0.29 (0.11)S	···	+0.08 (0.11)I	···	+0.00 (0.13)I
Ca	6.36	[CaI/FeI]	+0.23 (0.06)I	+0.21 (0.06)I	+0.23 (0.08)I	+0.15 (0.06)I	+0.02 (0.06)I
Sc	3.10	[ScII/FeI]	−0.11 (0.14)I	−0.16 (0.16)I	+0.05 (0.24)I	···	−0.81 (0.18)I
Ti	4.99	[TiI/FeI]	+0.03 (0.08)S	−0.14 (0.06)S	+0.38 (0.09)S	+0.11 (0.07)S	−0.06 (0.11)S
—	—	[TiII/FeI]	−0.15 (0.08)S	−0.35 (0.09)I	+0.31 (0.24)S	+0.42 (0.13)S	+0.04 (0.12))S
Cr	5.67	[CrI/FeI]	−0.03 (0.13)S	+0.33 (0.16)I	−0.06 (0.32)S	+0.08 (0.14)S	···
Mn	5.39	[MnI/FeI]	−0.35 (0.10)I	−0.40 (0.08)I	−0.34 (0.15)S	−0.35 (0.09)I	−0.39 (0.10)I
Co	4.92	[CoI/FeI]	+0.15 (0.29)S	+0.04 (0.15)S	+0.03 (0.23)S	···	−0.12 (0.13)S
Ni	6.25	[NiI/FeI]	−0.12 (0.16)I	−0.08 (0.09)I	−0.02 (0.12)I	−0.03 (0.09)I	−0.32 (0.09)I
Cu	4.21	[CuI/FeI]	−0.67 (0.14)I	−0.60 (0.16)I	+0.39 (0.24)I	−0.60 (0.13)I	−0.39 (0.13)I
Zn	4.60	[ZnI/FeI]	−0.24 (0.14)I	+0.08 (0.16)I	···	−0.31 (0.18)I	···
Y	2.24	[YII/FeI]	−0.57 (0.09)S	−0.52 (0.14)I	+0.63 (0.22)S	−0.62 (0.13)S	−0.59 (0.09)I
Ba	2.13	[BaII/FeI]	−0.05 (0.08)I	+0.56 (0.11)I	+0.93 (0.14)I	+0.15 (0.11)S	+0.29 (0.13)S
Nd	1.50	[NdII/FeI]	+0.10 (0.10)I	+0.23 (0.11)I	+1.08 (0.18)S	+0.28 (0.18)I	+0.24 (0.13)I
La	1.22	[LaII/FeI]	−0.27 (0.08)I	−0.09 (0.13)S	+1.24 (0.17)S	+0.22 (0.17)S	+0.13 (0.16)S
Eu	0.51	[EuII/FeI]	+0.26 (0.14)I	+0.33 (0.16)I	+0.61 (0.24)I	+0.54 (0.18)I	+0.54 (0.18)I

See Table 8 for Table Notes

Table 12. Comparisons between MOOG/MARCS and ATLAS/WIDTH for Scl-459

Elem	MARCS/MOOG (This paper)	ATLAS/WIDTH	ATLAS/WIDTH & VALD gf's
O I	7.39	7.32	7.39
Na I	4.34 (0.20)	4.42 (0.14)	4.46 (0.10)
Mg I	6.28 (0.20)	6.26 (0.08)	6.31 (0.02)
Al I	<5.11	<5.19	<4.96
Si I	6.11	6.18	6.18
Ca I	4.94 (0.15)	4.94 (0.10)	4.99 (0.11)
Sc II	1.45	1.42	1.53
Ti I	3.28 (0.12)	3.18 (0.27)	3.27 (0.23)
Ti II	3.32 (0.15)	3.23 (0.15)	3.40 (0.05)
V I	2.40 (0.51)	2.48 (0.35)	2.48 (0.33)
Cr I	3.80 (0.04)	3.78 (0.02)	3.78 (0.02)
Mn I	3.39 (0.08)	3.57 (0.08)	3.57 (0.08)
Fe I	5.86 (0.15)	5.98 (0.15)	5.97 (0.15)
Fe II	5.87 (0.15)	5.78 (0.18)	5.74 (0.15)
Co I	3.39	3.49	3.49
Ni I	4.70 (0.18)	4.75 (0.19)	4.78 (0.23)
Cu I	1.50 (0.15)	2.03 (0.09)	2.03 (0.08)
Zn I	3.11	3.05	3.02
Y II	0.53 (0.21)	0.47 (0.16)	0.47 (0.16)
Ba II	0.80 (0.15)	0.75 (0.13)	0.74 (0.13)
La II	−0.52 (0.09)	−0.52 (0.06)	−0.52 (0.03)
Nd II	0.19 (0.11)	0.16 (0.07)	0.20 (0.01)
Eu II	−0.52	−0.54	−0.54